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CRAZED RESIN FILTRATION OF COMBINED SEWER OVERFLOWS

Hercules, Incorporated
Cumberland, Maryland

October 1968

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Crazed Resin Filtration of Combined Sewer Overflows

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U.S. DEPARTMENT OF THE INTERIOR ● FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

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Crazed Resin Filtration of Combined Sewer Overflows

A Self-Adjusting and Self Cleaning Filter Feasibility Study

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Allegany Ballistics Laboratory
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ABSTRACT

This study was conducted with the support of the Federal Water Pollution Control Administration under Contract 14-12-39 to evaluate the feasibility of a self-adjusting and self-cleaning filter proposed for use on combined sewer systems to remove a large portion of suspended solids from sewage influent during storm flow conditions. Increased sewage flows during storm conditions in most combined sewer systems dictate that most or all of the flow be diverted from treatment facilities directly to the receiving body because the flow exceeds the treatment capacity. If a large amount of the solids can be removed before discharge to the receiving water, a major part of the pollutional load would be removed. — to pink sheet (opp. page)

The experimental filters tested in this program were cylindrical structures about one foot in diameter by one foot in length. The raw sewage influent is at the top, the filtrate comes through the cylindrical walls, and the concentrate is discharged through a bottom discharge. The materials of construction were fibers laid down in predetermined patterns by a winding process and bonded in place by resins. The porosity of the structure is imparted by a mechanical cracking or crazing of the resin with care being taken not to rupture the fibers which hold the body together. The self-adjusting feature is achieved by pressurizing the structure slightly (as in a water head buildup during storm flow) to slightly enlarge the pores. Water and a small amount of very fine suspended solids pass through the structure, leaving behind a more concentrated suspension of solids. The filtered water is then discharged to the receiving body. Upon release of the pressure, the pores close to shut off all flow through the walls and to divert the entire flow through the normal treatment operation.

In contrast to normal filters where a filter cake is allowed to build up, the self-cleaning feature is achieved by forcing the sewage flow to create a hydrodynamic scouring action against the smooth cylindrical walls to keep the solids from building up. Thus, a large part of the water goes through the walls, while most of the sewage solids remain suspended in the concentrate stream which is then passed through the normal treatment plant.

Design goals for the filter system were as follows:

(1) A filtration rate of 7 gpm/ft^2 of filter surface. This rate would be needed to design filters of such a size that they would be compatible with the available space in typical sewage treatment plants.

(2) A ratio of influent sewage flow to concentrate flow of ten to one, the difference between influent and concentrate being the filtrate flow (very low in suspended solids) which would pass through the filter wall and be discharged into the receiving body.

(3) A filtration system which could be continuously operated for two to three hours under storm flow conditions without plugging.

(4) Sufficient design data to allow scale-up to an operational filter.

The study consisted of an experimental fabrication and testing program, which was supported by structural design analysis, and a theoretical hydraulic analysis directed toward developing hydrodynamic design parameters to aid the self-cleaning feature of the filter.

Filters were designed which had an initial filtration rate with tap water of 25 gpm/ft^2, considerably over the design rate with the low pressures (4 psi) required for the proposed filter operation. The fabrication technique needed for this filtration rate was achieved near the end of the program, and it was not possible to evaluate such filters extensively with raw sewage during the program. However, sufficient data and fabrication techniques were developed to be able to reliably design filters with these filtration rates.

Although the design ratio of ten to one of influent to concentrate was not achieved, one experimental run showed a ratio of four to one of influent to concentrate for a short time at the beginning of the test. Solids content of the filtrate was 62% less than that of the influent, indicating the degree of improvement in discharge quality to be expected from this system. Although this was probably the best experimental result obtained during the program, two factors should be pointed out. The filter (04B) was one of the early ones, and as such had relatively few pores and also relatively coarse pores which, when plugged, gave low filtration rates. Filters developed toward the end of the program should give both higher filtration rates and a greater reduction in solids content in the filtrate due to the greater number of pores and the smaller pore size. The second factor to be pointed out is that this filtration rate, as in all of the runs, could not be maintained because of plugging of the filter, and the filtration rate gradually decreased during testing.

This plugging, mostly by fibers in the early filters and by slime in the later finer porosity filters, is the major unsolved problem in developing the filter concept. Data developed during experimental testing showed that the hydrodynamic cleaning in conjunction with mechanical flexing of the filter walls would in effect maintain or renew original filtration rates. Several concepts were advanced to utilize these data to devise alternate self-cleaning concepts in which the hydrodynamic scouring action is augmented by mechanical flexing (automatically controlled) of the filter walls. Such a concept is currently being evaluated in an independent research and development investigation.

Although the self-cleaning capability was not demonstrated, it was shown that the hydrodynamic self-cleaning approach would give partial cleaning of the filter. If the hydrodynamic self-cleaning approach can be successfully augmented by an automated mechanical flexing operation, indications are that continuous operation of the filter should be possible.

If the alternate self-cleaning approaches are successful in maintaining the required filtration rates, then it is highly probable that successful self-cleaning, self-adjusting filters can be developed. This statement is based on the results that show that the salient features of the filter except self-cleaning were achieved during the program. The desired filtration rates and suspended solids reduction can be achieved and would enable the filters to be used in combined sewer operations, either at the treatment plant or at outfalls in the sewer system.

An analysis of the storm flow influent to the Bowling Green Waste Treatment Plant was made and showed a 20-fold increase in solids content during the initial flush while the flow rate tripled.

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INTRODUCTION

Pollution of natural waterways by sanitary sewage from communities has become an increasingly serious problem as the population grows and moves to urban areas. The sewerage systems receiving combined sanitary and storm flows are a major source of this pollution. Waste treatment plants serving these systems are designed to provide adequate treatment for normal conditions; however, storm flows are frequently many times normal influent rates and exceed the plant capacity for treatment. During these periods, the plants are forced either to overload their treatment facilities, thereby reducing efficiency, or to bypass a portion of the excess flow without treatment. Either choice increases pollutional loading to the receiving waters.

The current solutions to the combined sewer problem are (1) to enlarge treatment facilities to handle these intermittent excessive loads or (2) to separate the sanitary and storm sewer systems. Both methods are extremely costly and usually not feasible.

The Hercules approach to the storm flow pollution problem is the use of a self-adjusting and self-cleaning filter that will concentrate the solids loading of the influent to a combined waste treatment plant by removing the surplus water that enters the system. The filtered water would then be chlorinated and discharged into the plant outfall, thereby reducing pollution of the receiving waters.

For some time it had been noted that filament-wound pressure vessels would leak at pressures well below failure pressures, and this leaking rate was found to increase directly with the amount of pressure applied. Microscopic examination of the interior surface of the vessels showed that the resin structure was cracked in a fine, random, hairline pattern, which has been termed "crazing." It was theorized that this inherent problem in composite filament wound structures could be used to advantage in developing an adjustable leak rate filter. This leak rate could be varied by controlling the expansion of the vessel which, in turn, was determined by the winding geometry and structural materials. The crazed resin would perform as the filtering medium. It was felt that these crazings or pores could be kept free from plugging materials by fluid flow induced shearing forces that would prevent formation of a filter cake. These factors formed the basis of the proposed self-adjusting and self-cleaning filter.

The original concept proposed use of low-modulus, high-elongation filaments helically wound and bonded in place with a thermosetting resin to yield a structure that would flex under low hydraulic pressures. The inner surface of the structure was to be coated with a smooth resin layer, or gel coat, that would craze and move with the supporting wound filaments, producing a permeable surface to allow passage of liquids at a rate proportional to the pressure applied. The shearing forces needed to keep the pores from blinding were to be supplied by a specially designed baffle body that would cause the solids containing concentrate liquid to constantly sweep the wall,allowing continuous filtration.

To reduce this concept to practice, Hercules has conducted a six-month study under FWPCA Contract No. 14-12-39 to demonstrate feasibility of the system. This work was necessary to advance the technology from construction of pressure vessels in which leaking is not desired to that of the filter where controlled pore opening and controlled leaking are the main principles involved. The goals set forth in this program were directed to producing a feasibility model and fully characterizing this model.

A schematic of the proposed method of filtration is shown in Figure 1. The filtering element is placed in line with the plant influent to serve as a conduit under normal flow conditions, passing the flow to treatment. During storm flow conditions, the increased flow increases the hydrostatic head in the filter. As the hydrostatic head increases, the filter structure expands, causing the wall to become permeable and allowing water to pass to the outer chamber where it flows to a chlorination chamber for treatment and subsequent discharge to the receiving water.

The rate of filtrate flow will depend upon the water level in the upper chamber, which reflects the rate of storm water entering the plant. Because of increased pressures, there will also be some increase in flow through the bottom discharge of the unit; however, this stream will be controlled within the limits of the treatment capacity of the plant. The solids removed by the filter element will be carried within the element to the bottom discharge and then to treatment.

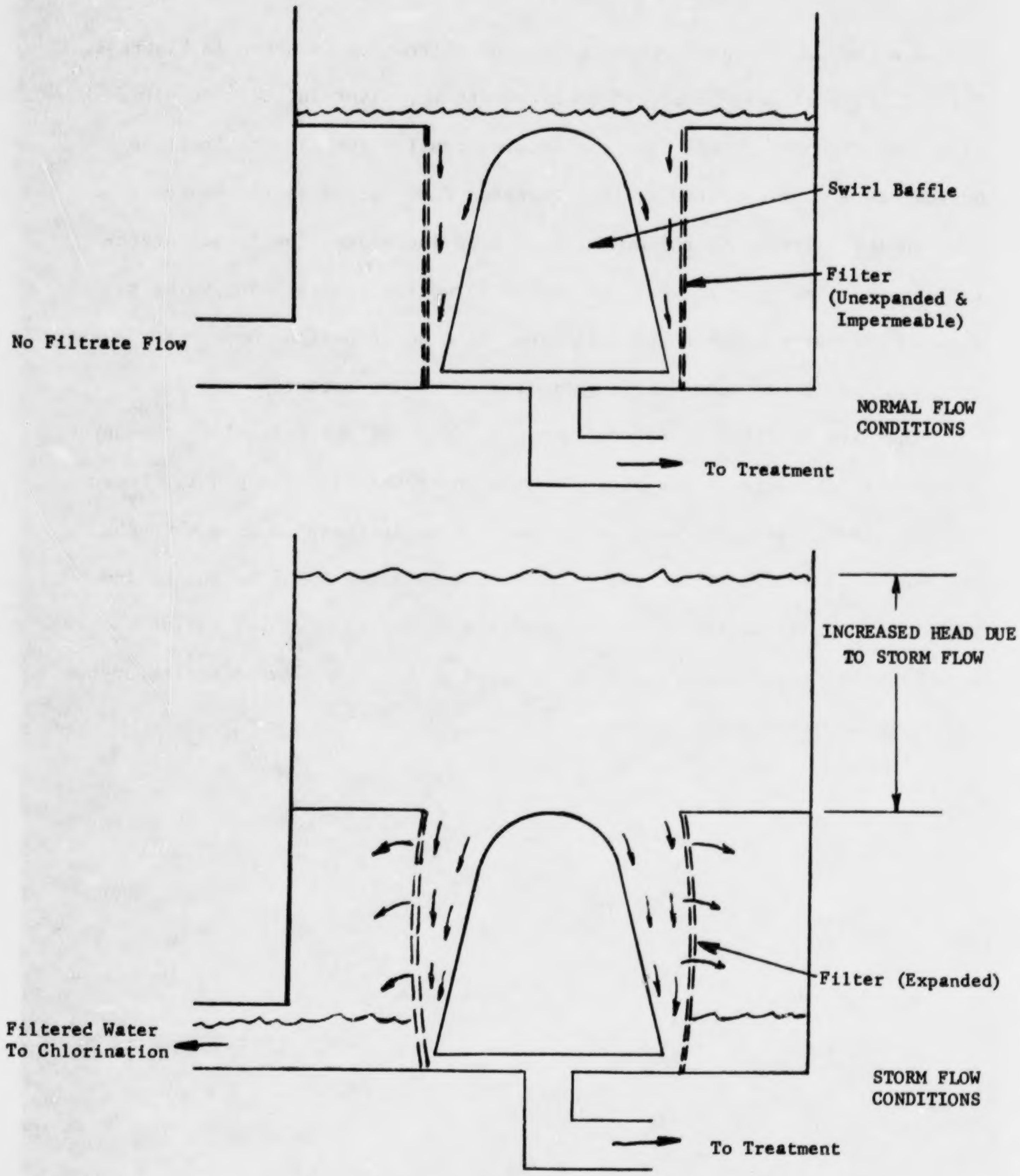
Swirl Baffle
Filter (Unexpanded & Impermeable)
No Filtrate Flow
NORMAL FLOW CONDITIONS
To Treatment
INCREASED HEAD DUE TO STORM FLOW
Filter (Expanded)
Filtered Water To Chlorination
STORM FLOW CONDITIONS
To Treatment

FIGURE 1

SELF-ADJUSTING AND SELF-CLEANING FILTER CONCEPT

SUMMARY

Problem and Approach

During storm conditions, the flow in a combined sewer system greatly exceeds the capacity of the treatment plant. Consequently, a part or all of the flow is diverted from the treatment plant directly into the receiving body, resulting in increased pollution. A large amount of the pollution caused in this manner is due to the suspended solids contained in the sewage. Expecially during the initial flush, the concentration of suspended solids can be 10 to 30 times higher than in normal flow, even with the dilution caused by the storm water. Normal filtration systems are not effective in removing suspended solids due to plugging of the pores.

As an approach to solving this problem, a self-adjusting, self-cleaning filtration system was conceived in which the incoming sewage is separated into two streams. One stream, the filtrate, is much the greater and passes through the filter, leaving the solids to build up in the smaller stream, the concentrate, which is directed through the normal treatment facilities. Filter cake build-up and resulting pore plugging are prevented by a hydrodynamic scouring of the filter walls by the sewage flow.

The areas of investigation included an examination of filter materials, structural analysis of the composite filter element, hydrodynamic analysis of the flow field, and experimental evaluation of test vehicles with domestic sewage.

Accomplishments and Results

This study was conducted to evaluate the feasibility of a proposed self-cleaning, self-adjusting filter concept for use on combined sewer systems. Conventional filters, when used to filter or strain raw sewage, plug very rapidly due to fiber and slime build-up in the pores.

In the present concept of a filter, a dynamic filtration system was evaluated in which the pores of the filter structure expand (very slightly) as pressure is applied as would happen during storm flow in a combined sewer system. As these pores open up, large amounts of water pass through the walls, including a small amount of very fine suspended or colloidal sewage solids. When the pressure is reduced as when a storm flow subsides, these pores contract and close, shutting off the flow of excess water through the walls and directing the full flow again to the treatment plant. This alternate opening and closing of the pores under slight pressure variation constitutes the self-adjusting feature of the filter.

In a conventional filter, all of the liquid passes through the walls or filter media and the solids build up as a cake. When raw sewage is passed through such a filter, complete plugging or blinding occurs very rapidly. In the current study of sewage filtration, a self-cleaning system is being developed to counteract this problem. In this concept, the filter is designed to eliminate buildup of a filter cake and the inflow is separated into two streams - the filtrate and the concentrate. The filtrate stream (designed to be up to ten times the flow of the concentrate) passes through the filter walls and, being very low in suspended solids, is treated by chlorination and passed directly into the receiving stream while the concentrate stream (designed to be one-tenth of the total flow) contains a high concentration of sewage solids and is directed through the normal sewage treatment plant process. To maintain the flow of water through the walls of the filter and to prevent plugging of the self-adjusting pores, a hydrodynamic self-cleaning technique is being evaluated. In this process, through the introduction of high flow rates on the influent side of the filter body, a hydrodynamic scouring action occurs to sweep the suspended solids away from the filter pores. By utilizing thin walls, alternate slight fluctuations in pressure effect variations in pore size and cause the particles which do become trapped in the pores to be swept on through with the filtrate. This constitutes the self-cleaning aspect of the system being studied in this program. Design goals for the pressure fluctuations are 2 to 4 psi, equivalent to a water head build-up of from about four to eight feet.

To combine these concepts into one filter, a filament-wound composite structure was conceived as the test vehicle. The filter on which most of the tests in this program were carried out, consisted of a cylindrical structure one foot in diameter and one foot long made from fibers (polypropylene, polyester, or fiberglass) wound in predetermined patterns and impregnated with liquid resins. Upon curing of the structure, the resins harden to give a self-supporting, thin-walled (about 0.1 inch or less) cylinder of fibers intertwined in a hardened resin matrix. End plates are applied to the structure, resulting in a thin-walled pressure vessel.

The desired porosity is imparted to the nonporous (at this point) structure by flexing the structure (mechanically or with pressurization), causing the resin portion of the structure to crack or craze into very fine openings with the fibers preventing complete rupture. These cracks then alternately open and close by the application or removal of slight pressure heads. The self-cleaning aspects of the filter are imparted to the structure by flow regulation, either by rate control into, through, and out of the structure, or by center body baffles or by a combination of these methods.

The study consisted of an experimental design, fabrication and testing program, which was supported by structural design analysis, and a theoretical hydraulic analysis directed toward developing hydrodynamic design parameters to aid the self-cleaning feature of the filter.

A design filtration rate of 7 gpm/ft^2 was selected as a goal during this work. This goal was selected on the basis of practical filtration units small enough for use in most combined sewer systems. For example, a combined sewer system with a normal flow of 100,000 gal/day might experience a ten-fold increase or up to 1,000,000 gal/day rate under storm flow conditions. It would be desirable to pass about 900,000 gallons of this flow through the filter. To do this at 7 gpm/ft^2 would require 90-100 sq. ft. of filtering area, equivalent to four 5 ft x 5 ft panels of filter surface or a cylinder a little more than 5 feet in diameter and 5 feet high. Engineering design would optimize size, shape, and placement of the filtering media to reduce the space required to a minimum.

Considerable effort was expended on developing fabrication techniques for the filters. The initial filters produced had relatively coarse crazing and relatively low filtration rates, while toward the end of the program, filters were produced with the desired fine crazing and very high filtration rates. All filters were first tested with tap water to establish the ultimate capability of the filter. (It was found that the tap water rate and the initial filtration rate with raw sewage were very nearly the same.) A 6 in.-dia. filter made with polar fiber windings was produced which had an initial filtration rate of 25 gpm/ft^2 at 4 psi and which passed no water at 0 psi. This filter was fabricated near the end of the program and was not completely tested. It was only possible to fabricate one 12 in.-dia. filter using the same technique as above.

Although it was not possible to completely reduce this filter concept to practice during the period of performance, the salient features of the concept, with the exception of self-cleaning, were demonstrated.

Filters were fabricated which were self-adjusting for varying water flows at pressures varying between 0 and 10 psi.

Fabrication techniques were developed to produce filters capable of filtration rates of 25 gpm/ft^2 at 4 psi, considerably above the design goal of 7 gpm/ft^2. This was achieved with a 6 in.-dia. experimental filter with polar windings.

One filter, 04B, was operated slightly under the design goal of 7 gpm/ft^2 for several minutes before plugging occurred. During this test, the ratio of filtrate flow rate to concentrate flow rate was approximately three to one. Suspended solids, as measured in the filtrate stream, were only 38% of the incoming stream. This filter did not contain the ideal porosity developed later but did clearly demonstrate the potential of the system.

Filters were reactivated with no additional treatment after being allowed to dry out with the pores plugged. Application of pressure to the filters after drying restored the original rates of filtration. This indicates the feasibility of on-off operation as would be experienced in intermittent storm flows.

The experimental studies did not include evaluations of the theoretical fluid flow analysis due to the timing in the program. Baffle designs and fluid flow rates were made on a "best guess" basis. All of the filters plugged after short periods of operation, showing the need for further work in the self-cleaning area. However, the following promising results were obtained:

1) The original filters had relatively coarse crazings and were found to plug with fibrous materials. The improved filters with fine crazing made toward the end of the program became plugged but more with slime than with fibrous materials. Solids passing through these filters also had much smaller particle size as shown by Coulter Counter particle size data.
2) A hydrodynamic lift-drag theory was developed which suggests that particles can be kept away from the filter wall, thus

helping to prevent plugging. This theory was not tested during the program.

3) Indications were that a purely hydrodynamic approach to self-cleaning would not be sufficient to keep the filters from plugging. Consequently, several approaches to a mechanical augmentation of the hydrodynamic cleaning feature were conceived. These concepts would also be capable of automatic operation and are based on momentary intermittent backflushing of the filters. Manual flexing of the filters tested during the program restored the flow after plugging had occurred, showing that this approach could be effective.

An analysis of the storm flow influent to the Bowling Green Waste Treatment Plant was made and showed that during the initial flush, the suspended solids content of the stream went from a normal content of 270 ppm to 4400 ppm within a two-minute period. For this storm, consisting of 0.25 inch of rain over 30 minutes, the flow rate went from the normal 250,000 gal/day to about 760,000 gal/day within 30 minutes after the storm began. Flow rate and suspended solids content returned approximately to normal about 2 hours after the end of the storm. This shows that while in a strict sense, the Bowling Green system is not a combined system (storm sewers do not purposely enter into the Sanitary System), there are unknown sources of storm water entering the sewer system, being both old, unmapped storm sewers and illegally connected downspouts. The effect is one of combined sewers except for the amount of grit and street washings which would normally be expected in a combined system. During the program, it was also determined that there was considerable ground water infiltration into the system during wet periods.

Additional experimental work is required before an operational demonstration unit can be designed. However, preliminary design concepts have been considered using assumed values where engineering data were not available to develop a preliminary cost estimate. This estimate suggests that a plant the size required by Bowling Green (0.1 MGD normal flow) could operate with the filter system for a $30,000 capital investment with yearly operating costs of about $950. In larger plants the operating cost appears to be about $0.01/1000 gallons of normal flow through the plant.

Conclusions and Recommended Future Work

Conclusions drawn from results of this study are as follows:

1) Filters were developed with the desired fine pores which had initial filtration rates greater than the design rate of 7 gpm/ft^2.
2) Techniques were developed to design and build filters with the desired fine porosity and high filtration rates.
3) In actual filtration runs, it was shown that suspended solids could be reduced by as much as 62%. This test was made with a filter having relatively coarse porosity, and indications were that filters having the very fine porosity developed toward the end of the program would have even better solids removal efficiency.

4) The original hydrodynamic self-cleaning concept was not completely demonstrated. However, the studies suggest that a lift-drag hydrodynamic cleaning with automatic mechanical flexing of the filter could achieve the self-cleaning function. Manual flexing of the filters during actual filtration runs restored the filtration rate after plugging had occurred.

5) Sufficient data were generated during the study to show promise that the filtration system could be used in combined sewer systems when the self-cleaning feature is achieved.

6) When the self-cleaning feature is fully developed, the filter system should be useful in combined sewer systems for concentrating solids in storm flows at the treatment plant and for installation at remote outfalls in a combined sewer system. Data were obtained to show that actual filtration rates almost four times the design goal were achievable. If the self-cleaning approach can be fully developed, such high filtration rates would be very useful for the installation of the filter in combined sewer treatment plants and at combined sewer outfalls.

7) Although the filter would not be applicable as a direct replacement for primary or secondary sedimentation because the concentrate would not be of sufficiently high solids content to be equivalent to primary sedimentation sludges, it would have potential in greatly reducing the size of sewage treatment plants by acting as a concentrator of raw or aerated sewage.

It is recommended that the following studies be conducted before an operational filter can be demonstrated:

1) Test the lift-drag hydrodynamic theory for particle impingement reduction on the filter walls as suggested by this study. (A disadvantage of this theory is that flow regulating pumps and other appurtenances would be required for the necessary flow control.)
2) Evaluate alternate methods of self-cleaning to be used in conjunction with the hydrodynamic cleaning of the filter. The methods suggested by this study are pressure cycling and momentary back-flushing utilizing a water-hammer effect.
3) Conduct a theoretical study of the filter design and fabrication techniques needed to make this filter economically feasible. A suggested approach which shows much promise is a filter consisting of insertable flat panels rather than a cylinder. The panels can be flexed and thus cleaned in either direction, thus greatly easing the self-cleaning problem. An additional feature would be the ease of replacement and repair.
4) A pre-pilot demonstration facility testing program to establish the features suggested above and to establish the economic requirements.

Hercules is currently carrying out feasibility testing of Items 1, 2, and 3 in an Independent Research and Development Program. When these studies are completed in about three months, a follow-on proposal will be submitted recommending the program to be followed to lead to a successful operating filter.

DISCUSSION

Program

Performance of the work on this program is reported in five sub-sections to allow treatment of the closely related areas. Because of the nature of the filter involved, each area is interdependent on the other areas and a number of items will be discussed in more than one sub-section. The overall program was geared to follow the plan presented in Hercules Incorporated's Proposal No. 14-12-39, Revision No. 1. This program is defined by the following goals:

1. Determine the configuration, winding geometry, types of fabrication materials, and methods of fabrication to yield a filter capable of opening at relatively low hydraulic pressures to pass filtered water and a small percentage of solid particles.
2. Determine the fluid mechanic requirements to produce the necessary forces along the interior walls of the filter element to provide effective self-cleaning action.
3. Build scale-model units and install them at the Bowling Green Waste Treatment Plant for filtering feasibility studies using municipal raw sewage.
4. Evaluate methods of eliminating, minimizing, and/or controlling slime growths and grease on the filter surfaces.
5. Perform preliminary analytical studies to measure velocity profiles and turbulence levels.
6. Estimate the potential capital and operating costs for a full scale filter operation.
7. Recommend an approach, based on the feasibility study, for full scale filter demonstrations.

8. Characterize the influent to a combined waste treatment plant during storm flow conditions.

To achieve these goals, materials were selected and evaluated, test structures were produced and tested, and a paper study was conducted to theoretically develop design parameters for a workable self-cleaning unit.

Several of the program goals were not fully achieved during the span of the program. In general, this was due to the problems of reduced filtration rates during filter testing with raw sewage where self-cleaning was only partly successful. This prevented any accurate cost estimate and necessitated a series of assumptions for the order of magnitude estimate provided. Also, a recommended program for full scale demonstration would be premature at this time since feasibility has not yet been demonstrated on all functions of this filter.

It should be noted that the design goal for filtration rate was 23 gallons per minute through the 3.14 square foot wall area of the scale model test element. This is equivalent to a filtration rate of just over 7 gpm/ft^2.

Materials Development

The selection of the materials for fabrication of the filters was based on desired mechanical properties and bonding characteristics. A study was performed in parallel with the fabrications to determine the effects of the operating environment on the candidate materials. This study was carried out by placing samples of the candidate material in the wet well of the municipal waste treatment plant. At intervals of 2, 8, and 16 weeks, the samples were removed, examined, washed with water, and tested to determine their mechanical properties. The examination and washing were steps in the evaluation of the types of growths and deposits formed and the ease of their removal. Due to the fibrous nature of the filaments, it was difficult to determine whether the sewage material was adhering or merely entrapped. The resin specimens were easily washed clean except for a few minor white deposits that occurred on the Epon 826 resin samples.

The initial candidate filaments, a polypropylene and a polyester, showed some sign of degradation due to the exposure. The polypropylene decreased 11% in tensile strength and 17% in elongation, while the polyester lost 28% in tensile strength and 14% in elongation. The effects of the exposure appear to occur during the early periods and then level off as though a resistant layer had formed on the filaments. The levels of degradation exhibited would have little adverse effect on any structure fabricated from these materials. Table 1 lists the results of the testing.

TABLE 1

Effect of Sewage on Candidate Filaments

Filament	Exposure Time (Weeks)	Tensile Strength (lbs)	Tenacity (g/denier)	Elongation (%)
Polypropylene	Control	6.59	4.75	30.5
Polypropylene	2	5.93	4.27	23.6
Polypropylene	8	5.62	4.05	23.6
Polypropylene	16	5.89	4.24	25.4
Polyester	Control	8.93	8.10	13.3
Polyester	2	6.96	6.31	11.5
Polyester	8	6.11	5.54	11.1
Polyester	16	6.40	5.80	11.4

The candidate resins were cast into ASTM D638 Type 1 tensile specimens, having long thin (1/4 in.) gage lengths to allow more surface exposure to the sewage. The high elongation resins were more seriously degraded than the lowest ones. The prime candidate, Epon 826 epoxy, suffered little effect from the sewage regardless of the curing catalyst employed. The tests results are shown in Table 2.

TABLE 2

Effect of Sewage on Candidate Resins

Resin System	Ingredients	Exposure Time (Weeks)	Tensile Strength (psi)	Elongation (%)	Modulus (psi x 10^3)
1	Epon 953A & B (100/16 pbw)	Control	1746	38.9	21.2
		2	1647	51.9	12.3
		8	1185	40.0	6.8
		16	1321	46.6	11.8
2	Epon 826/DETA/ Cab-O-Sil (100/11/3 pbw)	Control	7890	2.7	284.6
		2	7643	3.0	247.8
		8	7193	3.0	216.7
		16	7908	2.7	338.4
3	Epirez-Epicure (10/7 pbw)	Control	1201	52.5	15.7
		2	696	51.8	4.7
		8	410	36.0	2.5
		16*	349	26.6	17.0
4	Epon 826/ZZL-0803 (100/37.5 pbw)	Control	4639	5.2	137.4
		2	9165	5.8	192.3
		8	8778	5.5	190.0
		16	8522	4.7	330.9
5	Epon 826/DETA (100/11 pbw)	Control	5013	4.7	114.6
		2	9379	5.1	246.9
		8	9547	5.9	186.9
		16**	9638	4.1	353.4
6	Epon 871/ZZL-0803 (100/82.5 pbw)	Control	61	21.5	0.385
		2	76	28.6	0.422
		8	80	25.0	0.378
		16	69	23.5	0.330

---

*Results of one sample only.

**Results of two samples only.

During the program a special high modulus, low elongation epoxy was formulated for use as a gel coat. The stoichiometry of the epoxy was unbalanced to yield a brittle smooth glassy coating that would craze in a very fine pattern. This epoxy was Epon 826 with Catalyst D. No sewage exposure tests were conducted due to short time remaining in the program.

The initial filters were fabricated using a two-resin system, one for the inner liner or gel coat and a second resin for winding the supporting structure. When bond failures occurred during crazing operations, a bondability study found that to prevent interface bond failures, similar resin formulations should be used and the first resin applied should not be completely cured prior to the application of the second. This was necessary since most of the resin strength is developed by chemical rather than mechanical bonding.

Colored polypropylene filaments were used in the filter fabrications since previous testing found the undyed material quite difficult to bond. The surface treatment required to color the filaments improves the mechanical bond quality. Studies were made to determine the bond strength developed between the candidate filaments and resins. The winding resins, Epon 953 and Epon 826, formed good quality bonds to the polyester and fiberglass and only fair bonding to the polypropylene (Table 3), with the exception of the bulk polypropylene (crimped fibers) to Epon 826 high strength bond.

TABLE 3

Filament-Resin Bondability Study

Filament	Tensile Strength (psi) Epon 953A & B	Tensile Strength (psi) Epon 826/ZZL-0803
Polypropylene (1050 denier)	310	263
Polypropylene (Bulk 3500 denier)	290	2050
Polyester	970	1250
Fiberglass	2200	3000

When difficulties in obtaining the desired crazing were encountered (see following section, "Filter Fabrication"), several filters were fabricated using fiberglass. The "S" or structural type fiberglass, which has good chemical and moisture resistant properties, was immediately available and was used for testing to prove the feasibility of high modulus fibers for this application. No environmental testing was done on the "S" fiberglass because insufficient time remained in the contract performance period.

Tests of composite samples of candidate filaments and resins in a sewage environment were not conducted since no acceptable quality test has been developed to determine degradation of thin walled structures which have been intentionally cracked in the manner required for this filtration study.

Filter Fabrication

The original concept of the self-cleaning self-adjusting filter was a filament wound structure in which bands of filaments are precisely wound over a rigid mandrel and bonded with a thermosetting plastic. These bands are positioned in a helical pattern, and netting analysis calculations are used to design the desired structural characteristics. Axial and hoop moduli of the structure are varied by choice of helix angle, number of wound layers and fiber-resin materials.

The model chosen to demonstrate the feasibility of this filter was a 12-inch diameter cylinder with a 12-inch long filtering area. The semi-rigid structure was composed of a filament wound shell and a permeable resin liner or gel coat. The gel coat was made permeable by cracking or crazing this resin liner. Calculations were made for each fabrication using the mechanical properties of the chosen materials and operating parameters to determine the winding requirements.

Figure 2 shows the mandrel set in the winding machine at the time of winding the first helical bands. In this arrangement, the individual strands (bundles of filaments) are pulled from storage spools by the rotation of the mandrel. Each strand passes through the funnel-shaped resin cup where the strands are wetted and positioned side by side into a band which is shown being wound on the mandrel. When the desired amount of material has been wound, hoop (or 90°) windings are placed over the structure at designated intervals to act as reinforcements or "doublers." These become the filter sealing and clamping surfaces (see Figure 3). It should be noted that the length of the mandrel was selected to produce two separate filter elements for each winding. After the assembly has been cured at an elevated temperature, a cut is made through the material at one end of the mandrel and the filters are stripped from the mandrel as seen in Figure 4. Cutting the filters to length completes the fabrication (Figure 5).

The first filter fabrication employed the low modulus polypropylene fibers to wind the reinforcement doubler areas. The residual strain in these fibers caused these areas to shrink after removal from the mandrel making attachment to the test stand quite difficult. To remedy this, the remaining fabrications were made using high modulus fiberglass roving for these doublers.

After fabrication of the first filter, it was found that the yarn did not spread in as wide a band as predicted, producing an open weave structure as shown in Figures 6 and 7. The inner resin liner or gel coat, if left unsupported by the winding filaments, will break and fall out after crazing leaving large holes through the filter wall. Yarn, as distinguished from roving, contains a twist in the filaments making up each strand. This twist prevents the individual filaments from lying side by side and forming a wide band; instead, it produces a rope effect. Fabrication calculations involve the number of filaments present in each unit area of the filter

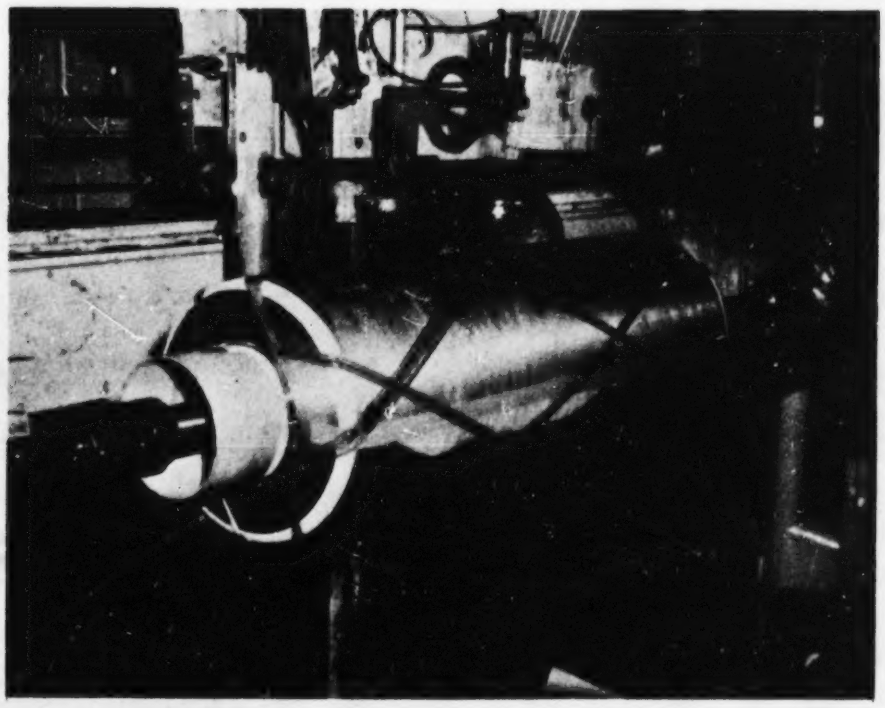

FIGURE 2
Filter Fabrication - Winding of First Helicals

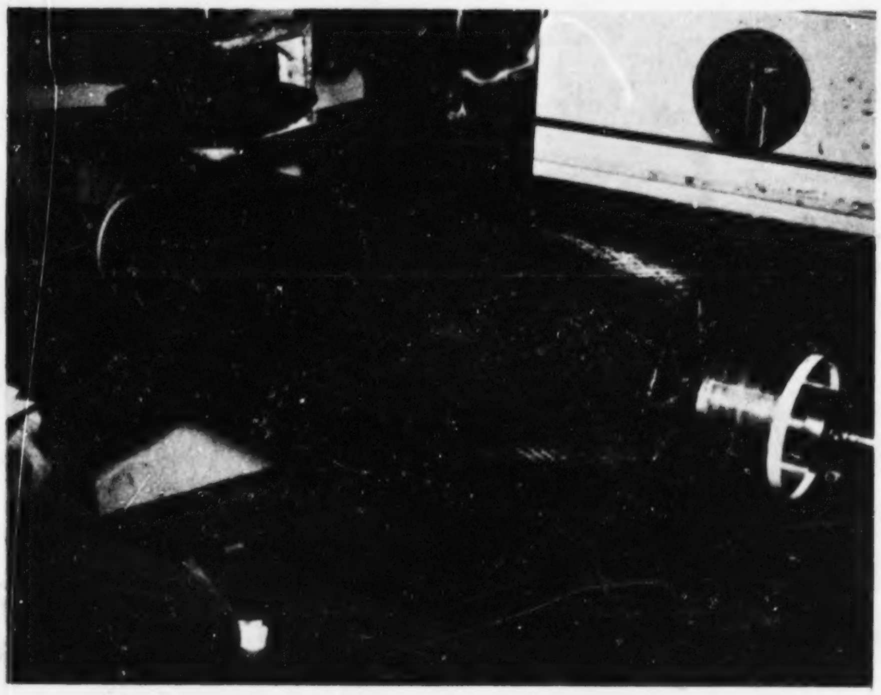

FIGURE 3
Filter Fabrication - Winding of Doublers

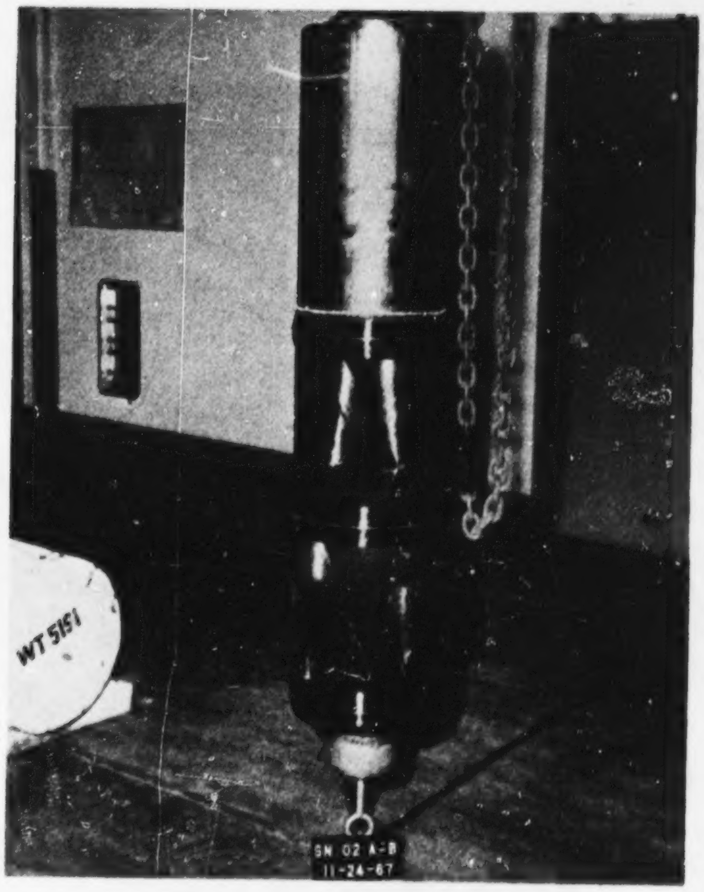
WT 5151
SN 02 A-B
11-24-67

FIGURE 4
Filter Fabrication - Stripping Filter from Mandrel

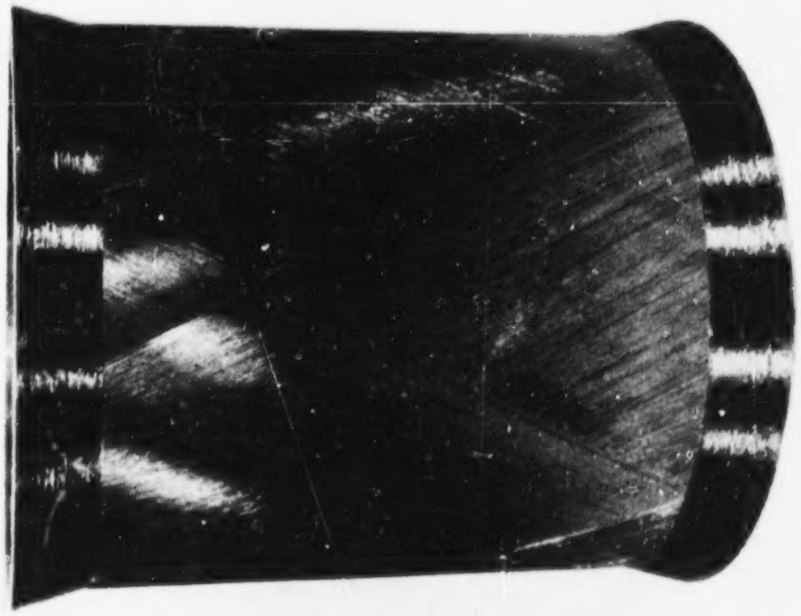

FIGURE 5
Filter Fabrication - Completed Filter

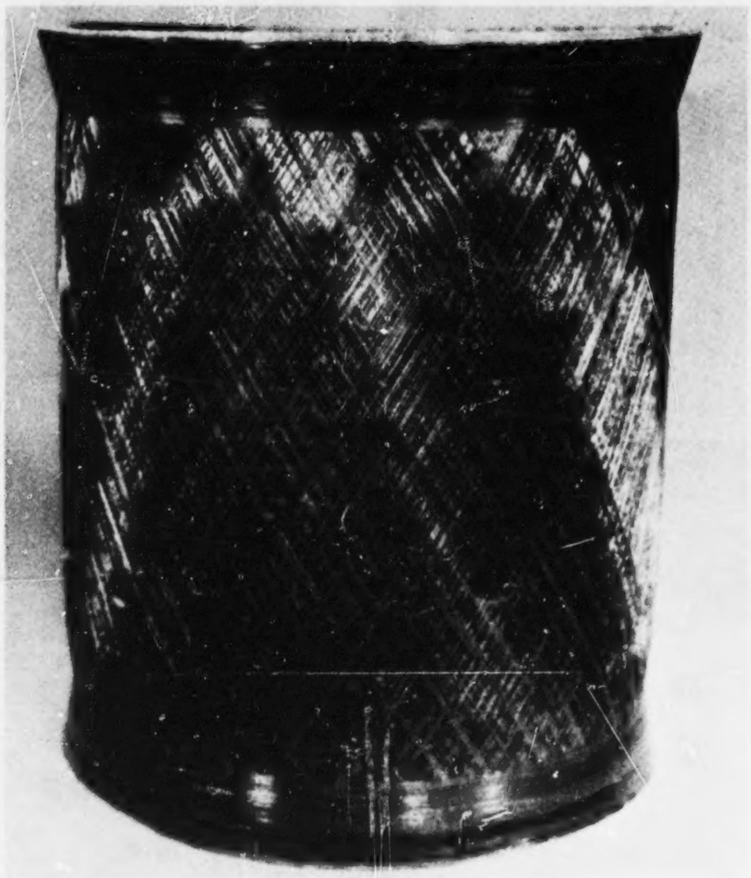

FIGURE 6
Filter 01A-Exterior View

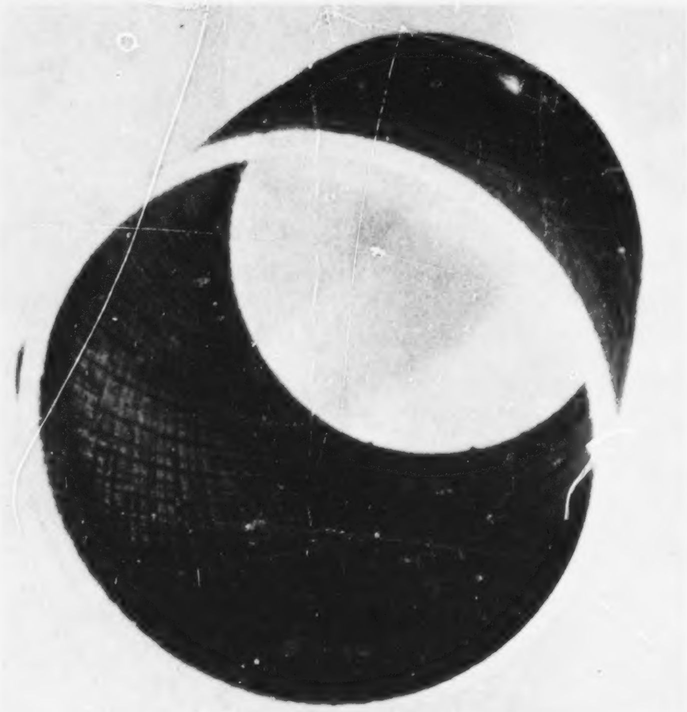

FIGURE 7
Filter 01A-Interior View

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walls, so for a fixed amount of material to cover a given area without leaving holes, the individual filaments must align themselves side by side to form a wide thin band rather than series of ropes. Commercial polypropylene-polyester fibers are intentionally given twist to make their handling easier and to prevent fraying. Later filters (as noted in Table 4) were fabricated with fibers which had the twist removed to yield a wider band.

The completed filter (Figure 5) shows an inherent feature of helical wound structures - the crossover - about one-third the length from the left doubler. This area is where the bands interweave. During crazing attempts, when cracks were opening along the helix or winding angle, the crazings were not produced at these crossovers, reducing the amount of filtration area. A different technique of fabrication was tried - convolute or polar winding - which forms no crossovers. In this type of winding, all the filaments in each ply lie parallel along the helix angle, and successive plies are placed at the negative angle to the previous layer.

The inner resin liner, or gel coat, was applied to the filter elements by two methods: (1) the resin was brushed onto the mandrel and partially cured before winding the filament structure; and (2) the resin was brushed on the interior of the completed filter element. The former method takes advantage of the pre-strain placed in the winding filaments by the fabrication technique, causing the gel coat to close tightly after the crazing or cracking operation. This causes the filter to act as a fluid conduit at low pressure. Gel coat thickness was varied to determine the amount required to produce the best crazing. With the first fabrications, gel coat thickness had no effect on crazing quality. All crazings were coarse.

During early crazing tests it was found that the gel coating had a tendency to break away from the wound structure. To overcome this, filters were fabricated using a single resin for both applications. Resulting filters were improved, but the problem was still present.

Producing the desired random hairline cracks, "crazing," proved to be a major problem in the filter fabrications. The desired crazing, exhibited by fiberglass pressure vessels, is shown in Figure 8. The first method used was to apply internal pressure to the filters while mounted on the test stand, rigidly supporting the ends of the filters. Pressurization rates varied from 2 to 25 psi/minute. The few resulting cracks were oriented axially (Figure 9). In an attempt to increase the amount of crazing, rapid pressurization was produced by use of a pyrotechnic device (explosive) in water filled filters. The cracks produced were still axially oriented but more frequent (Figure 10). Figure 11 shows the separation of the gel coat from the supporting structure that occurred during early crazing attempts. Since the structures have a higher modulus in the axial direction than in the hoop direction due to the filament helix angle, axial loading was applied to the filters during internal pressurization to strain the gel coat more uniformly. The resulting crazings were oriented along the fabrication helix angle. Another method used was to mechanically break the gel coat with rollers and hammering devices. The crazings produced were random but not as numerous or fine as desired. During fabrication of filter 04A and B, the gel coating was allowed to cure until hard and the surface scratched with coarse sandpaper to cause stress lines; then the structure was wound over the preconditioned gel coat. The stress lines had no effect on the crazing pattern produced. The gel coat of filter 10A was reinforced with a polyester cloth to support any pieces which might break free from the wound structure.

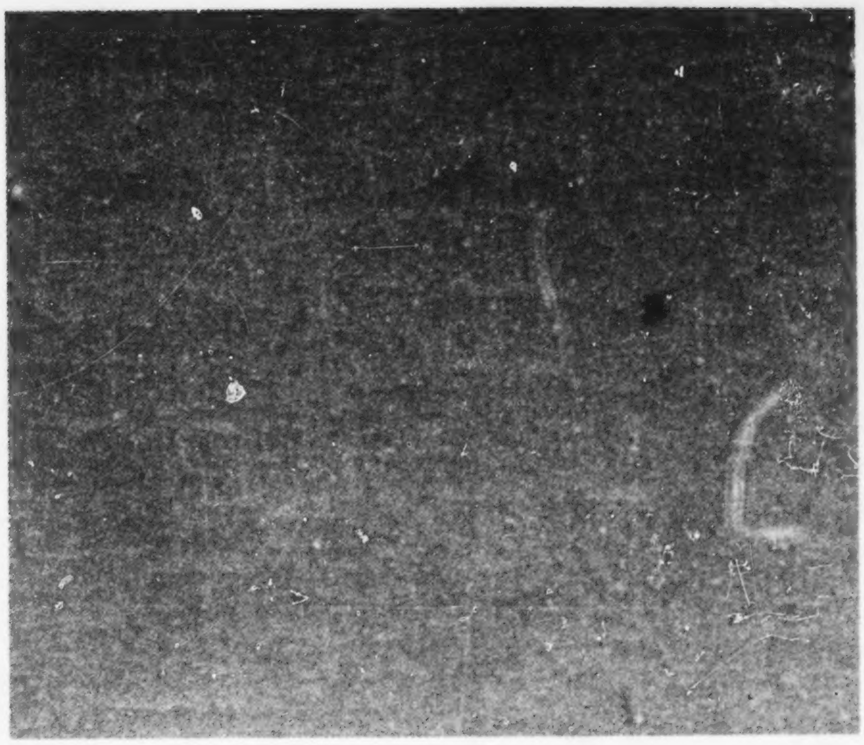

FIGURE 8
Desired Crazing (10X)

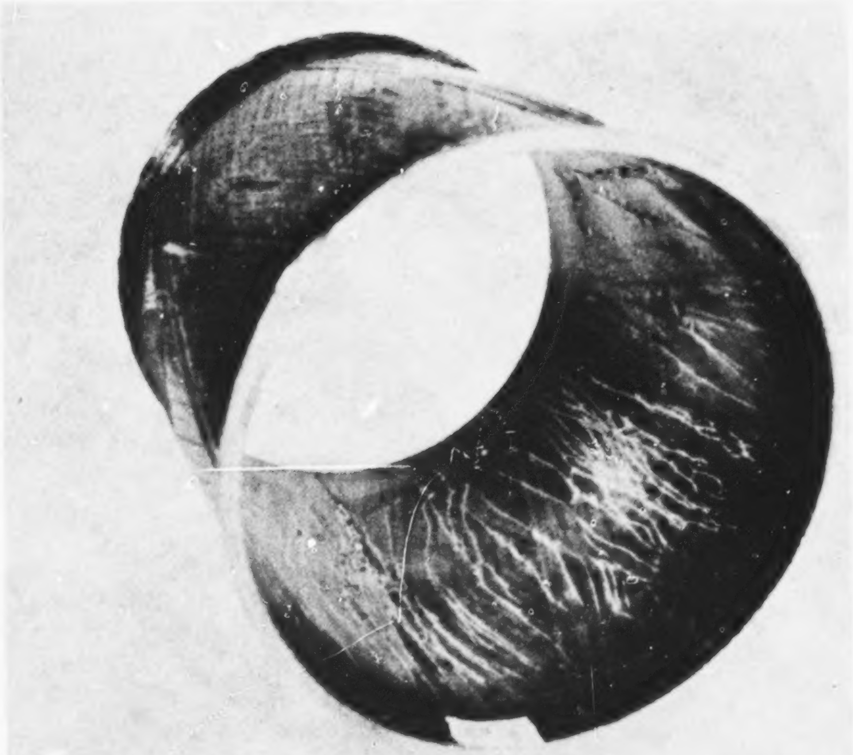

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FIGURE 9
Axial Crazing (Filter 04A)

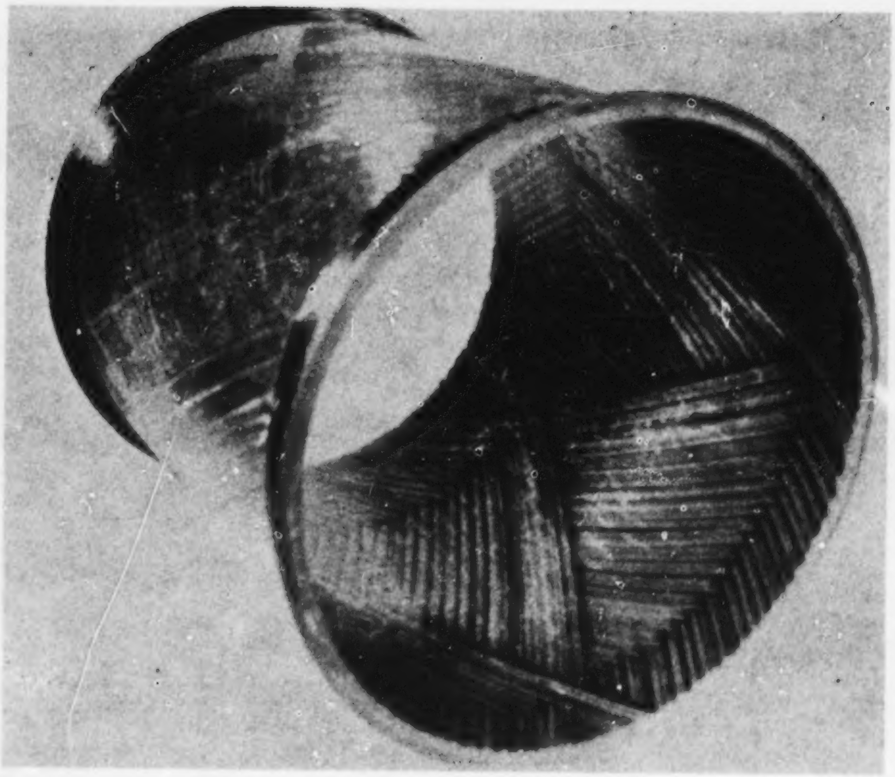

FIGURE 10
Rapid Pressurization Crazing (Filter 03A)

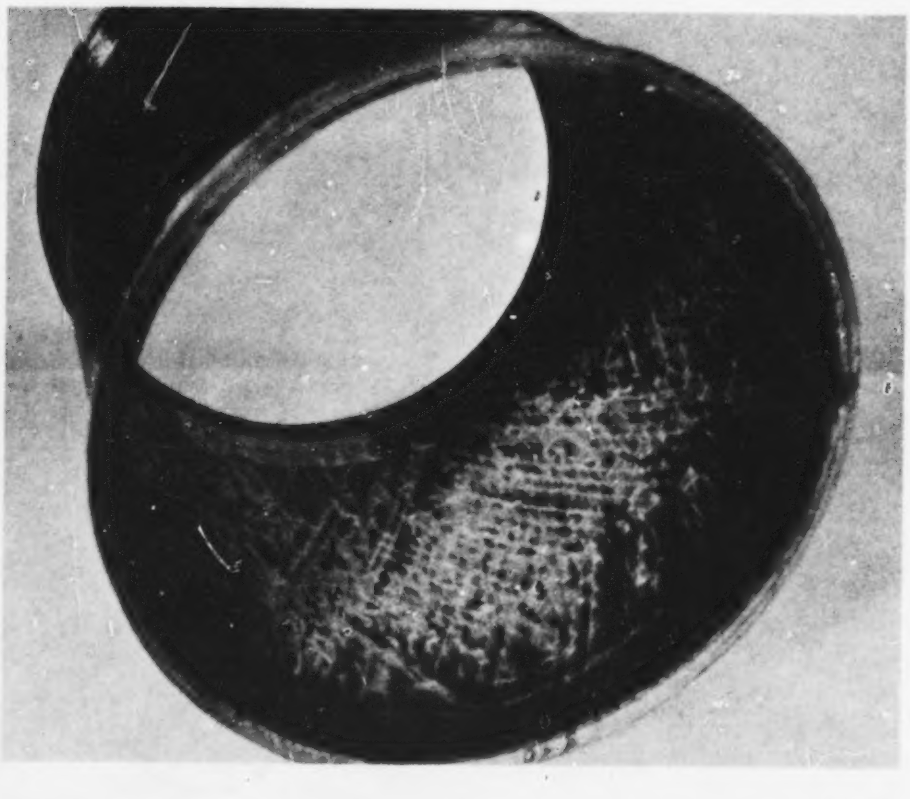

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FIGURE 11
Crazing and Gel Coat Separation (Filter 03B)

This cured gel coat was cracked before overwinding by placing a wire cloth over the coated mandrel and hammering on wire cloth. The star-like cracks remained in the gel coating after fabrication was completed but the cloth failed during internal pressurization, leaving larger than desired cracks in the gel coat.

Micromechanical analysis of the crazing problem produced the following results: (1) A high ratio of fiber modulus to resin modulus causes a strain factor favorable to production of cracks parallel to each fiber and around (or across) each resin-encapsulated fiber. (2) A higher number of cracks will be produced by reducing the fiber diameter and increasing the number of fibers used in fabrication. (3) The helical interweaving method previously being used should be changed to a convolute or polar pattern, eliminating crossovers within each layer. (4) Use of a high modulus fiber will result in a structure whose expansion is less, opening any cracks in the structure to a lesser degree.

The recommendations of this analysis were used in fabricating filter 12A and B and several sub-scale 6-inch-diameter, 6-inch-long filter elements. The analysis also indicated that slow rate pressurization (0.1 psi or less/min) would help increase the number of cracks. Filter 12A was crazed in this fashion but as each crack opened, the strain was relieved in the adjacent areas, resulting in few cracks oriented along the helix angle. Filter 12B (see Figure 12) and the sub-scale filters were crazed by mechanically flexing the structures parallel to their longitudinal areas and then slowly pressurizing. The crazing produced were quite fine, numerous and oriented along the fibers. These were the fine cracks sought.

The summary of filter fabrications in Table 4 shows the progression of changes made as tests were performed to produce crazing and to determine operating characteristics in the sewage environment. Major changes were

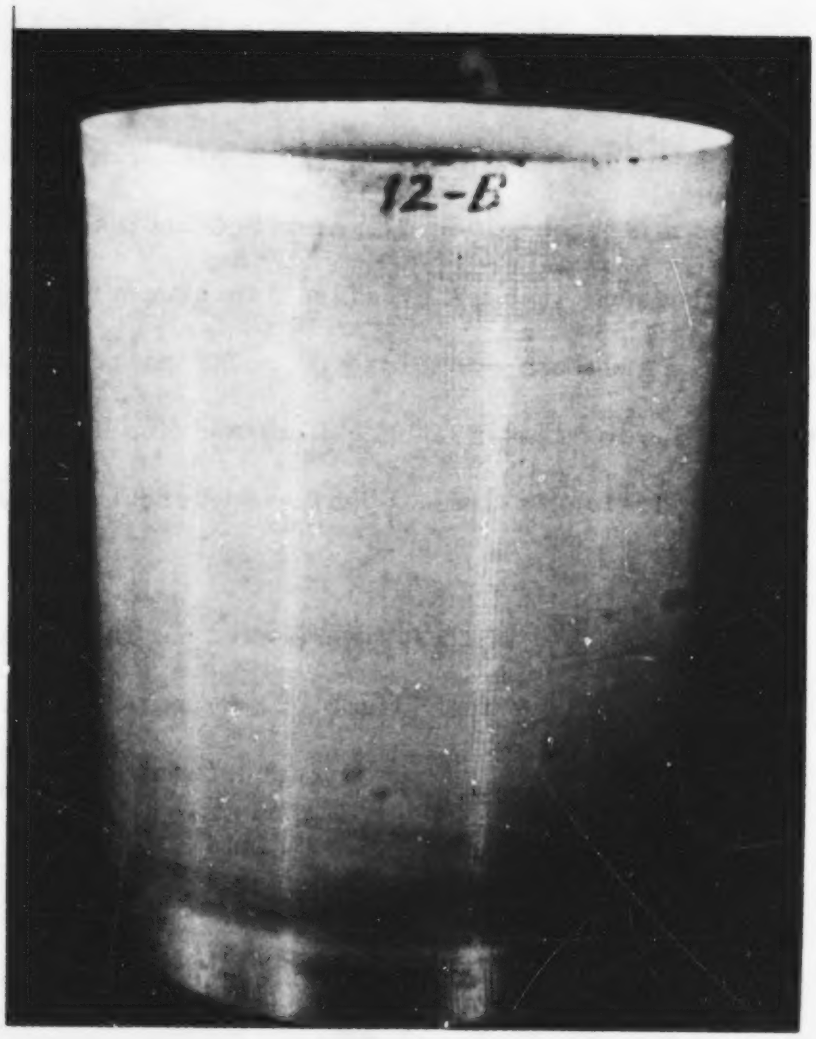

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FIGURE 12
Filter 12B-Exterior View

TABLE 4

Summary of Filter Fabrication

Filter Number	Fiber	Winding Resin	Gel Coat Resin	Winding Angle	Gel Coat Thickness	Crazing Method	Results
01A	Polypropylene (1050 denier)	Epon 953 A&B	Epon 826/DETA	30° - 5 layers	6-7 mils	Rapid	Pyrotechnic sizing
01B		" " "	" "	" "	"	Rapid	Pyrotechnic sizing
02A	Polypropylene (1050 denier)	Epon 953 A&B	Epon 826/DETA	26° - 2 layers	16-17 mils	Med & Rapid (Air)	Gel cast separation
02B		" " "	" "	" "	"	Rapid (Hot Water)	Few axial cracks
03A	Polypropylene (1050 denier)	Epon 953 A&B	Epon 826/DETA	26° - 2 layers	6-7 mils	Rapid (Cold Water)	Few axial cracks
03B		" "	" "	" "	"	Rapid	Few axial cracks & gel coat separation
04A	Polypropylene (1050 denier)	Epon 953 A&B	Epon 826/DETA	15° - 2 layers	6-7 mils	Rapid	Medium axial cracks
04B		" "	" "	" "	"	Rapid	Medium axial cracks
05A	Polypropylene	Epon 826/ZZL-0803	Epon 826/ZZL-0803	15° - 1 layer + 90° overwind	6-7 mils	Rapid	Coarse axial cracks
05B	(Bulk-3500 denier)	" "	None	" "	None	Slow	Coarse axial cracks
06A	Fiberglass (S-994 Roving)	Epon 826/ZZL-0803	Epon 826/ZZL-0803	15° - 2 layers	6-7 mils	Slow with axial compression	Helical cracks, structural failure
06B		" "	None	" "	None	Slow cycling	Helical cracks
07A	Polypropylene (1050 denier-low twist)	Epon 826/ZZL-0303	Epon 826/ZZL-0803	15° - 2 layers	6-7 mils	Slow	Doubler unbonding
07B		" "	None	" "	None	Slow	Doubler unbonding
08A	Fiberglass Cloth and Fiberglass	Epon 826/ZZL-0803	Epon 826/ZZL-0803	15° - 1 layer	6-7 mils	Slow 0-60 psi cycles	Helical failure
08B		" "	None	" "	None	--	--
09A	Polyester (1050 denier-low twist)	Epon 826/ZZL-0803	Epon 826/ZZL-0803	15° - 2 layers	6-7 mils	Very slow, hoop reinforcement	Coarse nelical cracks
09B		" "	Epon 826/DETA	" "	"	Very slow	Coarse helical cracks
10A	Polypropylene	Epon 826/ZZL-0803	Epon 826/ZZL-0803 & polyester cloth	15° - 2 layers	6-7 mils	Slow	Random cracks, cloth failures, reinforced with 90° P STR overwinds
10B	(1050 denier-low twist)	" "	Epon 826/ZZL-0803	" "	2-3 mils	Slow and mechanical flexing	Fine random crazing
11A	Polyester (1000 denier-low twist)	Epon 953	Epon 826/Cat. D	15° - 2 layers	6-7 mils	Slow and mechanical flexing	Coarse random cracks
11B		" "	None	" "	None	None	Curing temperature caused distortion
12A	Fiberglass Tape	Vendor Proprietary	None	11° - 4 plies-convolute or Polar	None	Ultra slow	Few helical cracks
12B	Fiberglass Tape and polyester	"	None	0° with 90° polyester overwinds	None	Ultra slow	Many axial cracks (BEST PATTERN PRODUCED)

made in the filament helix angle, reducing the angle to increase flexing and thus the filtration rate and finally changing to the fabrication technique suggested by the analysis. Material changes also reflect the difficulties experienced in obtaining optimum crazing. The two-resin system was replaced by a single resin used for both the filament bonding and gel coat functions to eliminate unbonding of the gel coat from the winding resin. Untwisted fibers to obtain a wider filament pattern and cloth reinforcement were used to provide support for the gel coat after crazing.

The final fabrications were made incorporating the information developed during the program. The crazing produced in Filter 12B possessed the fine pores sought, although they were not randomly oriented as was previously believed desirable. The cracks produced were numerous but the number was below the expected level. The resulting filter required a higher pressure to operate than was theoretically predicted for such a structure.

The knowledge gained from these fabrications provides sufficient information for recommendations to be made for pilot demonstration models containing the features of self-adjustment to hydraulic pressure and a fine crazing pattern.

Fluid Dynamics

The test vehicle selected for this program was a cylinder. Selection was based primarily on ease of fabrication of the filter elements and the related test equipment. In this program self-cleaning was approached from two directions. With the cylindrical test vehicle an experimental approach was made based on the intuitive principle that cleaning will be promoted by achieving the highest possible shear flow over the filter surface. The second approach was the theoretical study which examined the influence of a flow field on a particle in the field.

To investigate self-cleaning experimentally, a smooth interior finish on the filter element and high washing action were the two parameters on which attention was focused. Normal fabrication techniques produced a smooth initial surface which remained essentially smooth after being made porous. High washing action was obtained by reducing the free area inside the filter with a "swirl baffle." This terminology came from the original concept of inducing a swirl flow for maximum fluid motion while moving longitudinally through the filter area. Swirl flow was also induced by a tangential feed at the top of the test apparatus.

Three smooth walled cone segments were fabricated to act as baffles and were sized to provide different flow velocities across the filter surface and also to allow acceleration or deceleration across the filter based on the filter passing 7 gpm/ft^2 (see Figure 13). Two other baffles were also constructed. One was a spiral ramp configuration intended to provide very high velocities along the wall (Figure 14) while the other was a rough surfaced cylinder (constructed of deck plate) intended to cause high turbulence (Figure 15).

Most favorable results were obtained with the smooth walled cone which produced the highest liquid velocity. Turbulence per se produced no noticeable beneficial effect. All attempts at swirling the fluid over the filter by tangential feed and/or use of the spiral baffle increased the tendency for solids buildup on the filter of any tests run. A flow directed straight along the wall with moderate velocity but little induced turbulence produces the best cleaning. When this flow field was used with a filter which had the finest porosity no fiber entrapment occurred and no solids buildup developed on the inside surface of the filter; however, blinding was caused by fine particle entrapment in the pores within the filter structure.

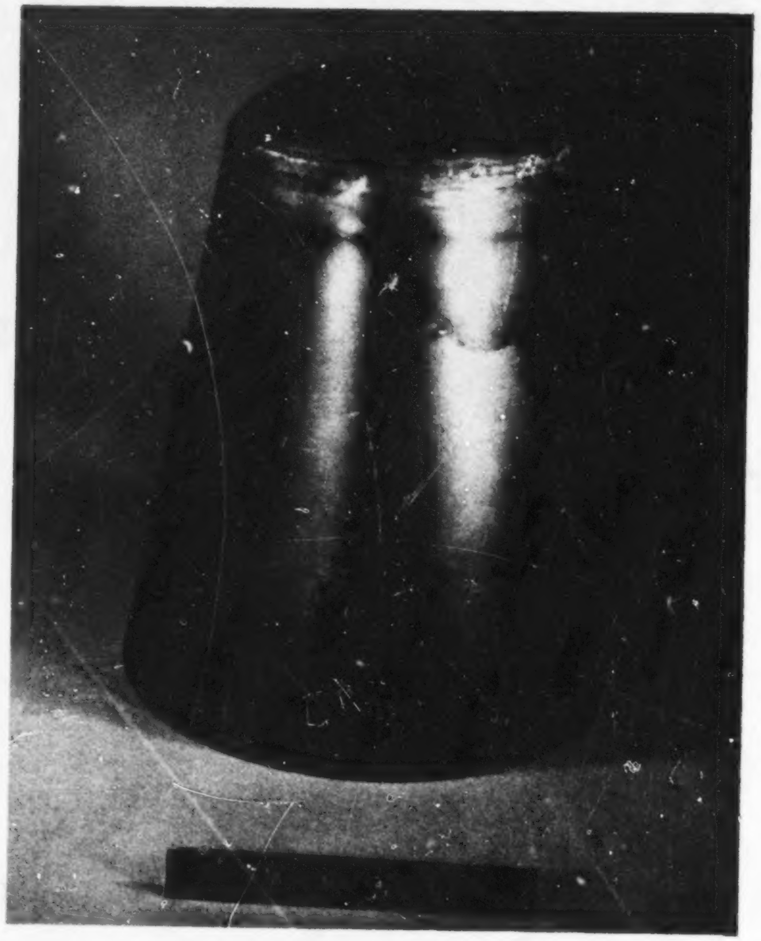

FIGURE 13
Baffle Body-10" x 6" Truncated Cone

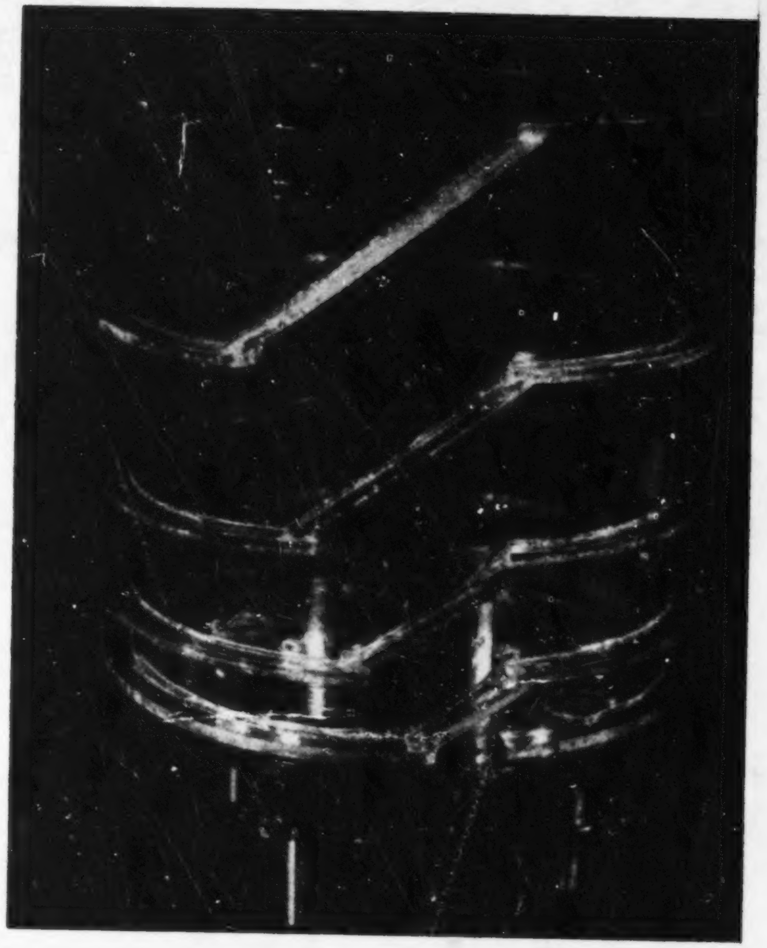

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FIGURE 14
Baffle Body-Ramp and Cylinder

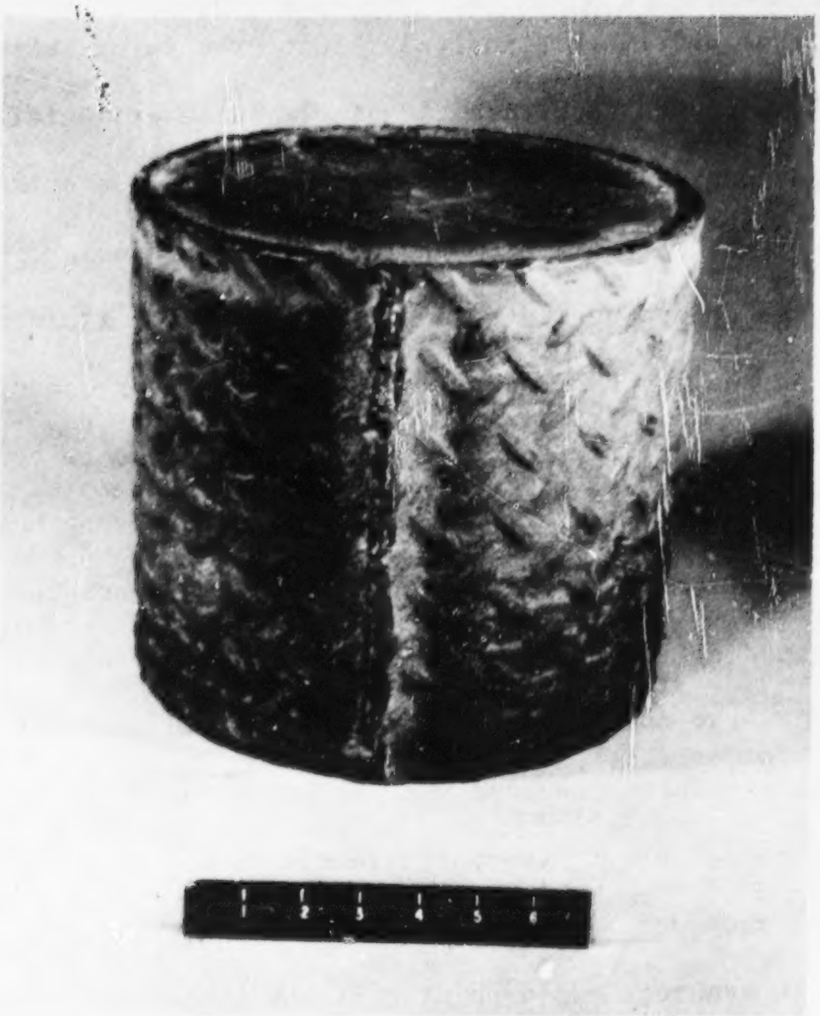


FIGURE 15 G-2140
Baffle Body - Deck Plate Cylinder

The analytical studies which were conducted in the support of the self-cleaning approach are discussed in Appendix A. Three different concepts are examined in this analysis. One or more of their combined effects can be directed to attain cleaning. These are briefly discussed below. The discussion here is limited to physical understanding and no attempt is made to consider the mathematics of the problem.

(1) Energy concept - If the distribution of the fluid energy is made uniform on the entire cross-section of the filter conduit, all suspended matter in the field including those adjacent to the filter wall will be forced to move along in the direction of the bulk fluid motion. Criteria for uniform distribution of energy are the uniformity of the velocity distribution and the thickness of the boundary layer. Thus, for the energy concept, the boundary layer development on the filter wall is carefully examined and the layer thickness is decreased to dimensions comparable to the particle dimensions to be filtered. As a consequence, such particles are not "encouraged" to come to rest at the wall for an eventual build-up of a filter cake.

(2) Particle lift concept - It can be shown that a particle trapped in a shear flow is acted upon by two forces. One is the drag force directed along the streamline and the other the lift force perpendicular to it. When this shear layer is realized in the boundary layer region, the lift force can be made to deflect the particle away from the boundary. The particle size which penetrates the shear region and arrives at the filter wall is a function of the fluid flow condition. Larger particles are kept in the concentrate flow stream. Thus, for a given flow condition, one can specify a filter which freely passes the smaller particles and thereby maintains clean filter operating characteristics.

(3) Particle migration concept - Again, the proper flow field is established for concentrating the particles away from the wall forming a ring in a pipe shear flow. This phenomenon has been observed repeatedly in the past and was recently examined in detail. Its application to filtration is examined here for the first time.

This analytical study (see Appendix A) has led to the following conclusions which are quoted: "The hydrodynamic approach to filtration and the associated dynamic cleaning at the wall of a filter are shown to be feasible concepts. It is shown also that optimum filtration schemes are obtained when the Reynolds number of the flow is great enough to establish a thin boundary layer over the surface of the filter. In particular, conical filter geometries and particle migration concept are found (analytically) to provide the best filtration schemes.

"Detailed methods for analysis and design of a filter are presented with particular illustrative examples. A computer program which solves the equation of particle motion in the boundary close to the filter surface and for various geometries is the most direct approach to the design problem."

Waste Water Characterization

The site chosen for the feasibility testing of the filters with raw sewage was the Bowling Green Waste Treatment Plant (BGWTP), Bowling Green, Maryland. This community is located about 5 miles from Allegany Ballistics Laboratory. The plant receives domestic sewage from approximately 2300 residents. No industrial wastes are included in the treatment plant influent. During dry weather, the average flow through the pump station is around 100,000 to 125,000 gallons per day, but during storm flow the plant may receive in excess of 700,000 gallons during a 24-hour period, with peak flow rates above 1 MGD.

Figure 16 shows the average dry weather flow plotted with the flow created

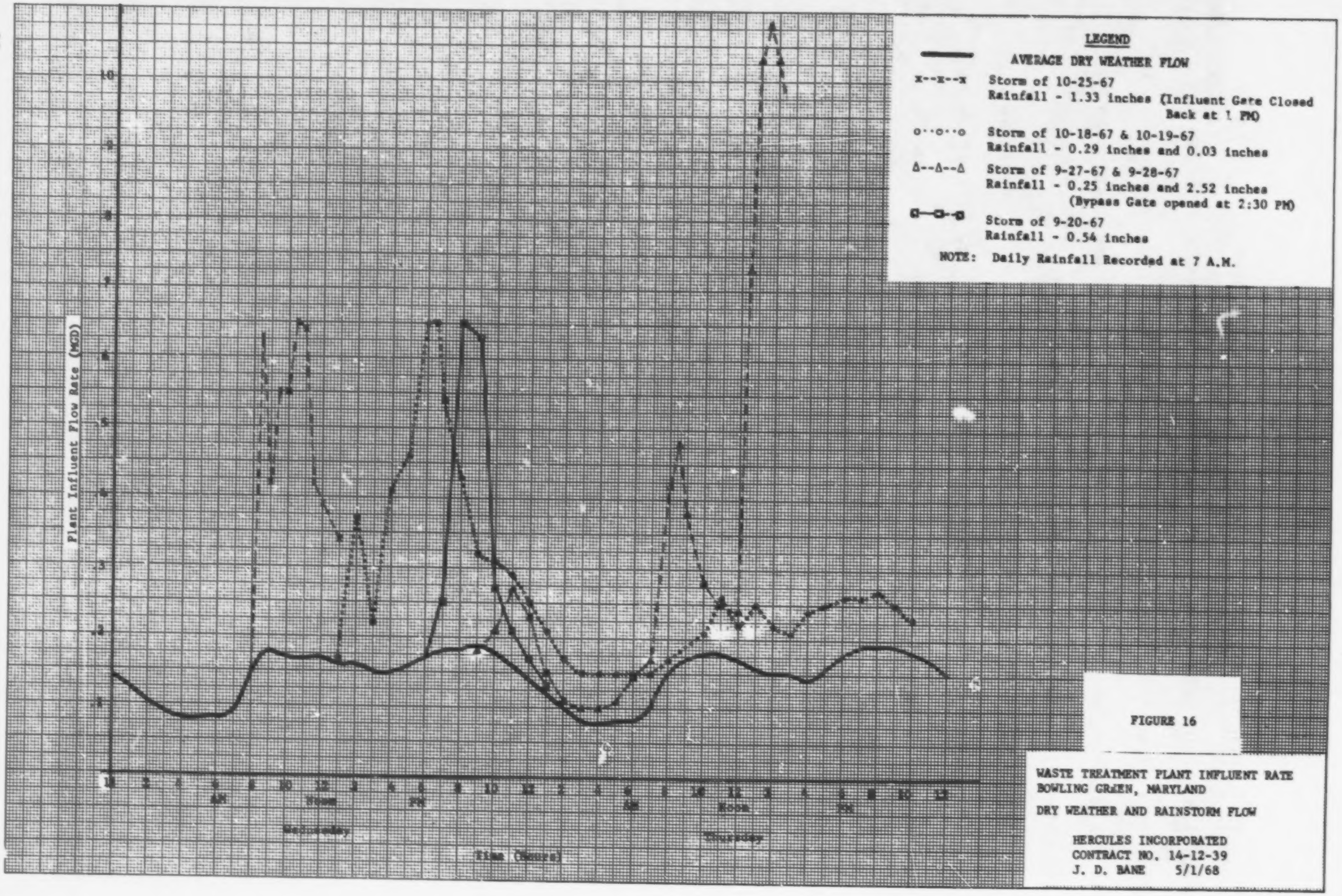


FIGURE 16

WASTE TREATMENT PLANT INFLUENT RATE
BOWLING GREEN, MARYLAND
DRY WEATHER AND RAINSTORM FLOW

HERCULES INCORPORATED
CONTRACT NO. 14-12-39
J. D. BANE 5/1/68

by several rain storms. Since rainfall is recorded locally only as a daily total, a 24-hour recording rain gage was transferred to this project for use in determining hydrologic versus plant influent data.

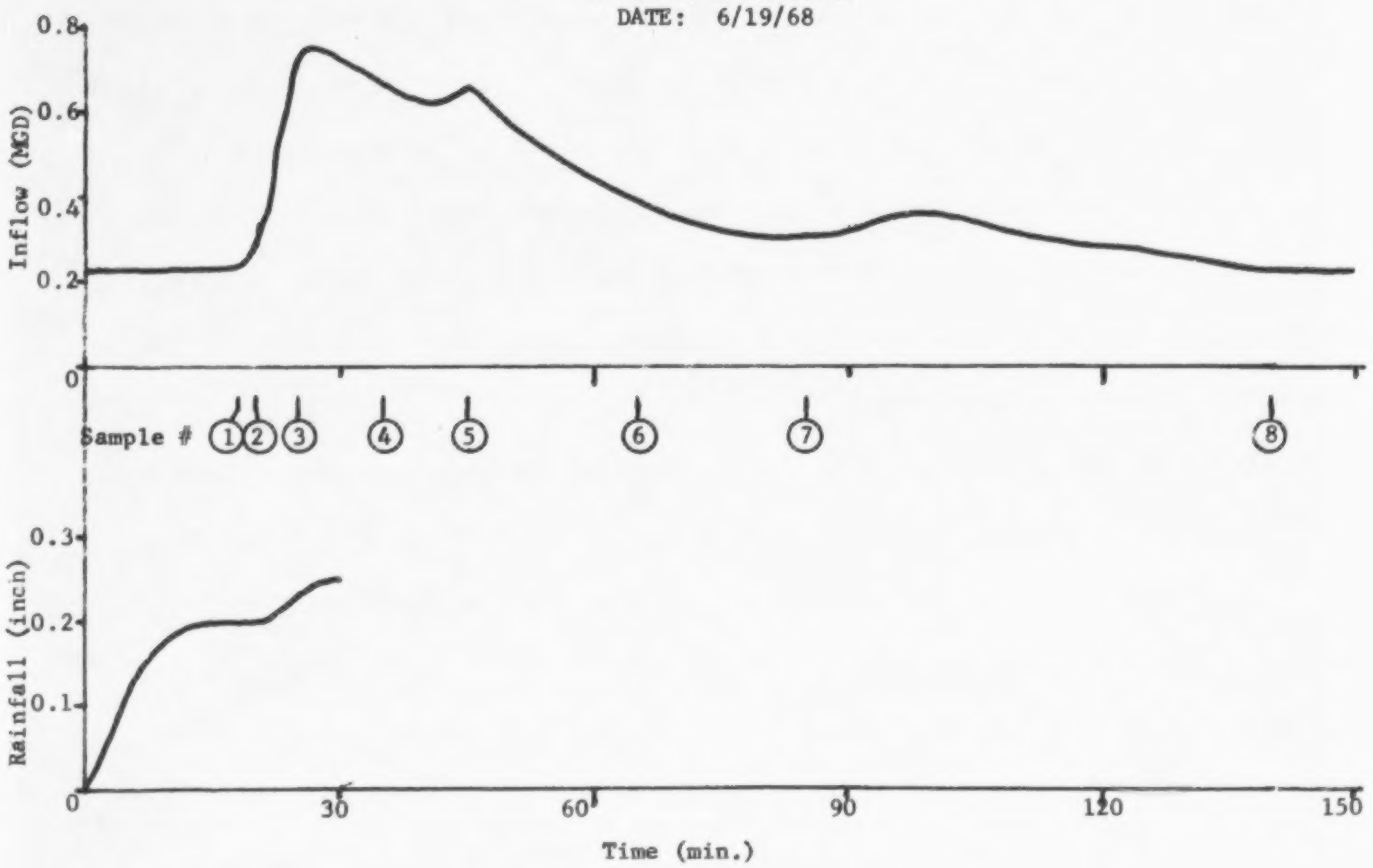
When this sewerage system was installed, an attempt was made to eliminate all connections except sanitary. Since the time of flow increase of the plant influent is approximately 30 minutes after the start of a rain, it appears that considerable runoff water is present. However, plant influent remains above normal for an extended period after a storm and rises during a snow melt, leading to the conclusion that infiltration into the lines also is significant.

During the contract negotiations, it was agreed that a characterization of this plant's influent would be made during the rise from normal to storm flow conditions. A sampling program was agreed upon and is presented in Appendix B. There were no rain storms during the early month of the performance period and then by the time the spring rains began, the influent was being diluted by the infiltration from the saturated ground (caused by the melting of a heavy snow) such that characterization at that time would have been meaningless.

On June 16, 1968, a rain storm producing 1/4 inch rainfall occurred after a dry period of 8 days. The BGWTP influent was sampled according to the plan. The hydrological and analytical data are presented in Figure 17. The initial sample obtained was gray and appeared to be normal late night flow, but after only two minutes the rate began to increase rapidly and the sewage became black and gave off a very strong odor, indicating septicity. This odor did not disappear until the flow again returned to nearly normal. The results of Sample No. 2 indicate the flushing of grit and putrescible material undergoing anaerobic digestion from the bottom

FIGURE 17

BOWLING GREEN WASTE TREATMENT PLANT
STORM FLOW ANALYSIS
DATE: 6/19/68



Sample No.	1	2	3	4	5	6	7	8
Time (min)	Normal	0	5	15	25	45	65	120
Flow Rate (MGD)	.25	.30	.76	.66	.66	.40	.32	.22
Total Solids (ppm)	655	4866	1765	1073	1268	731	534	722
Total Solids- Volatile (%)	41.9	55.8	X	40.1	X	41.5	42.9	52
Susp. Solids (Gooch) (ppm)	274	4383	1652	838	1179	436	190	390
(Glass) (ppm)	380	4678	1500	792	1208	459	163	392
Susp. Solids- Volatile (Gooch) (%)	86.5	57.4	41.7	51.1	56.4	56.4	64.2	72.3
(Glass) (%)	86.0	36.2	46.8	52.9	48.6	61.2	79.7	76.8
BOD (ppm)	204	1410	183	198	130	185	102	162
COD (ppm)	500	7400	X	X	X	X	X	X
pH	7.2	6.5	7.0	7.0	6.8	7.1	7.3	7.0
Immediate Oxygen Demand (15 min) (ppm)		42						

X - No analysis.

of the sewers. The samples taken during the high flow conditions after the initial flush indicate the presence of large quantities of grit.

A composite sample of the plant influent taken over a 4-hour period during relatively normal flow was analyzed to be used in characterizing the sewage to which the materials were exposed during their environmental testing. The results of these analyses of raw sewage are tabulated as follows:

Source	Suspended Solids	Suspended Solids-Volatile	Total Solids	Total Solids-Volatile	BOD	COD	pH
Raw Sewage (4-hour Composite)	153	124	590	344	115	228	7.3

All analyses reported were determined using the procedures outlined in the Twelfth Edition of "Standard Methods for the Examination of Water and Waste Water," with the exception of suspended solids determination. This variation, approved by the FWPCA, involves the use of fiberglass filter elements**, rather than the standard Gooch crucible technique.

Particle size distribution of the solids in the sewage was determined by a Coulter Counter. This device is an electronic instrument which measures particle size by circulating a conductive liquid containing the solid particles through an orifice. Liquid conductivity is measured across the orifice. The change in conductivity caused by a particle passing through the orifice is then related to the particle size. As the liquid circulates, the counter tabulates the size and number of particles passed. Raw data developed by the counter is reduced by computer to give a normalized and standardized size distribution readout which can be displayed by conventional methods.

** Whatman Glass Paper, grade GFC. "Rapid Solids Determination using glass fiber filters" Bruce M. Wyckoff. "Water & Sewage Works" Nov. 30, 1964, Reference Number, pg. R-349.

Coulter Counter samples are separated into several size ranges to allow accurate readout from an individual orifice. Normally the range of sizes for which a single orifice is used is about one order of magnitude. Sewage samples have utilized two ranges, 3 to 50 μ and 50 to 200 μ. The sample is filtered to remove large size particles for the lower range. The small particles (below the size desired for a run) do not interfere with counter operation, and data reduction analytically ignores these sub-range size particles.

Table 5 illustrates the type of computer output obtained from a test run. These data are then plotted by a standard "Weight Percent Greater Than vs. Size" method, as shown in Figures 18 through 21.

Filter Feasibility Testing

Two locations were prepared for use in the feasibility testing of the filters. The first test site, located at Allegany Ballistics Laboratory (ABL), is used for initial testing with water and simulated sewage (cellulose acetate particles) to determine filtration rates, produce crazing, and measure effects of swirl baffle body designs. The second test site is the municipal waste treatment plant at Bowling Green, Maryland (BGWTP). This plant is described in the Wastewater Characterization section of this report. A schematic layout of the BGWTP testing facility is shown in Drawing 60225N10001. The raw sewage for the feasibility testing was removed from the force main by tapping the blind flange used to cap the connection for a future pump installation. This tap is shown in the upper right hand side of Figure 22. The sewage is piped to a screener housing a removable basket having 1/4-inch openings. After passing through the test stand, the filtered and concentrated flows are fed into a common flume and pumped back to the plant wet well. The test equipment utilized 30° V-notch weir boxes for measurement of the concentrate and filtrate flows (see Figure 23). The test site at the BGWTP was designed and equipped to handle two filter test stands simultaneously.

TABLE 5

COULTER COUNTER DATA
(Test #1443-10)

Sequence	Lower Threshold Particle Diameter (Microns)	Interval Weight (%)	Weight Percent Greater Than (%)	Midpoint Particle Diameter (Microns)	Interval Frequency (%)	Cumulative Frequency (%)
1	146.36	0.0	0.0	167.542	0.0	0.0
2	116.17	0.1992	0.199	132.978	0.0000	0.0000
3	92.20	0.1992	0.398	105.545	0.0000	0.0001
4	73.18	0.3984	0.797	83.771	0.0002	0.0003
5	58.08	0.9959	1.793	66.489	0.0010	0.0012
6	46.10	5.5771	7.370	52.772	0.0109	0.0122
7	36.59	19.5197	26.889	41.885	0.0764	0.0885
1	29.07	0.0978	26.987	33.282	0.0008	0.0893
2	23.08	0.7819	27.769	26.416	0.0122	0.1015
3	18.32	3.7142	31.483	20.966	0.1159	0.2174
4	14.54	6.3532	37.836	16.641	0.3964	0.6138
5	11.54	8.9922	46.829	13.208	1.1222	1.7360
6	9.16	9.3832	56.212	10.483	2.3419	4.0779
7	7.27	9.5787	65.790	8.320	4.7815	8.8594
8	5.77	8.4058	74.196	6.604	8.3920	17.2513
9	4.58	10.1651	84.361	5.242	20.2968	37.5482
10	3.63	15.6386	100.000	4.160	62.4518	100.0000

Total Particles Counted - 32,845,744

Mean Diameter (Microns) - 5.14

Specific Surface Area - 0.65355 m^2/g

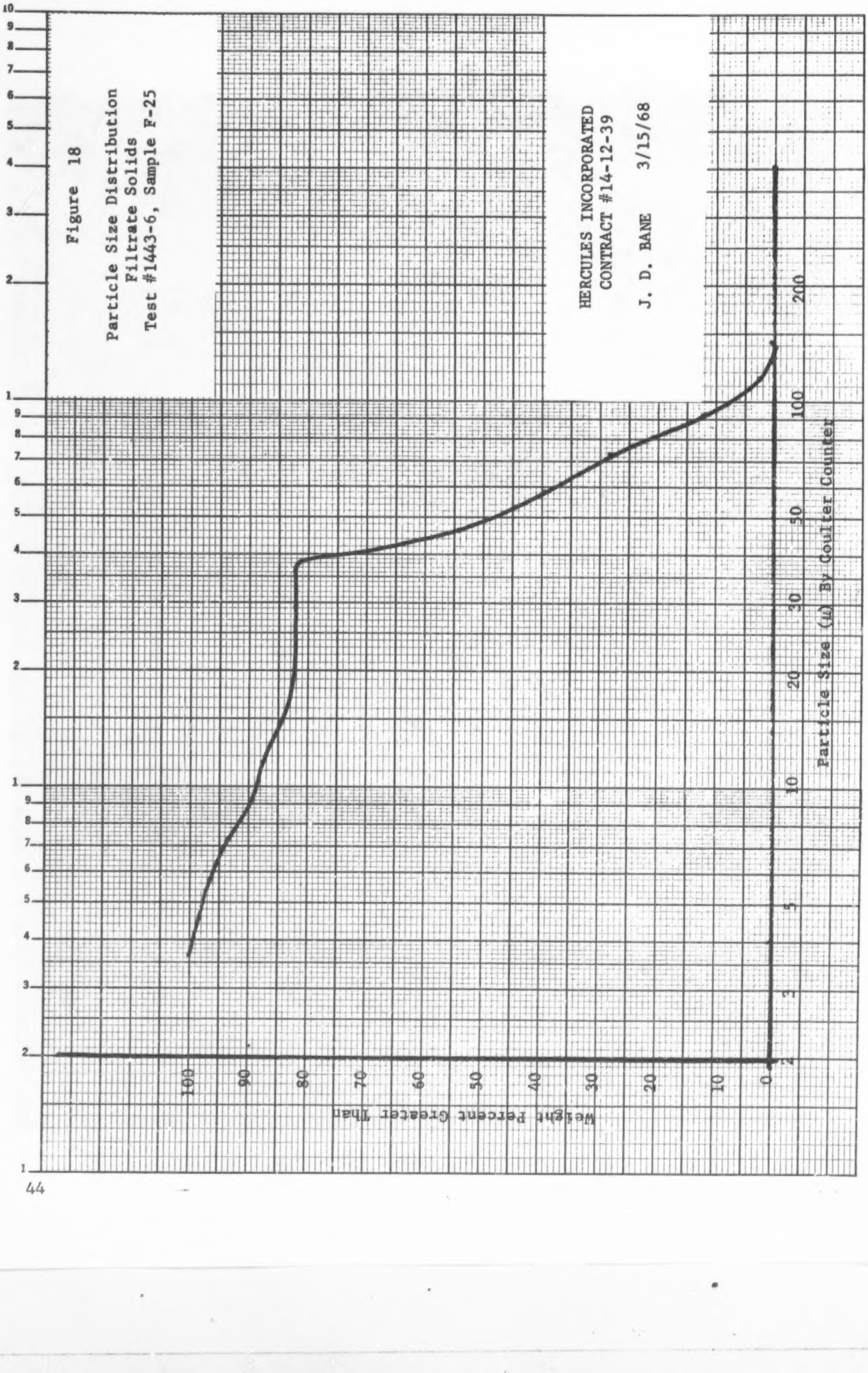


Figure 18

Particle Size Distribution
Filtrate Solids
Test #1443-6, Sample F-25

HERCULES INCORPORATED
CONTRACT #14-12-39

J. D. BANE 3/15/68

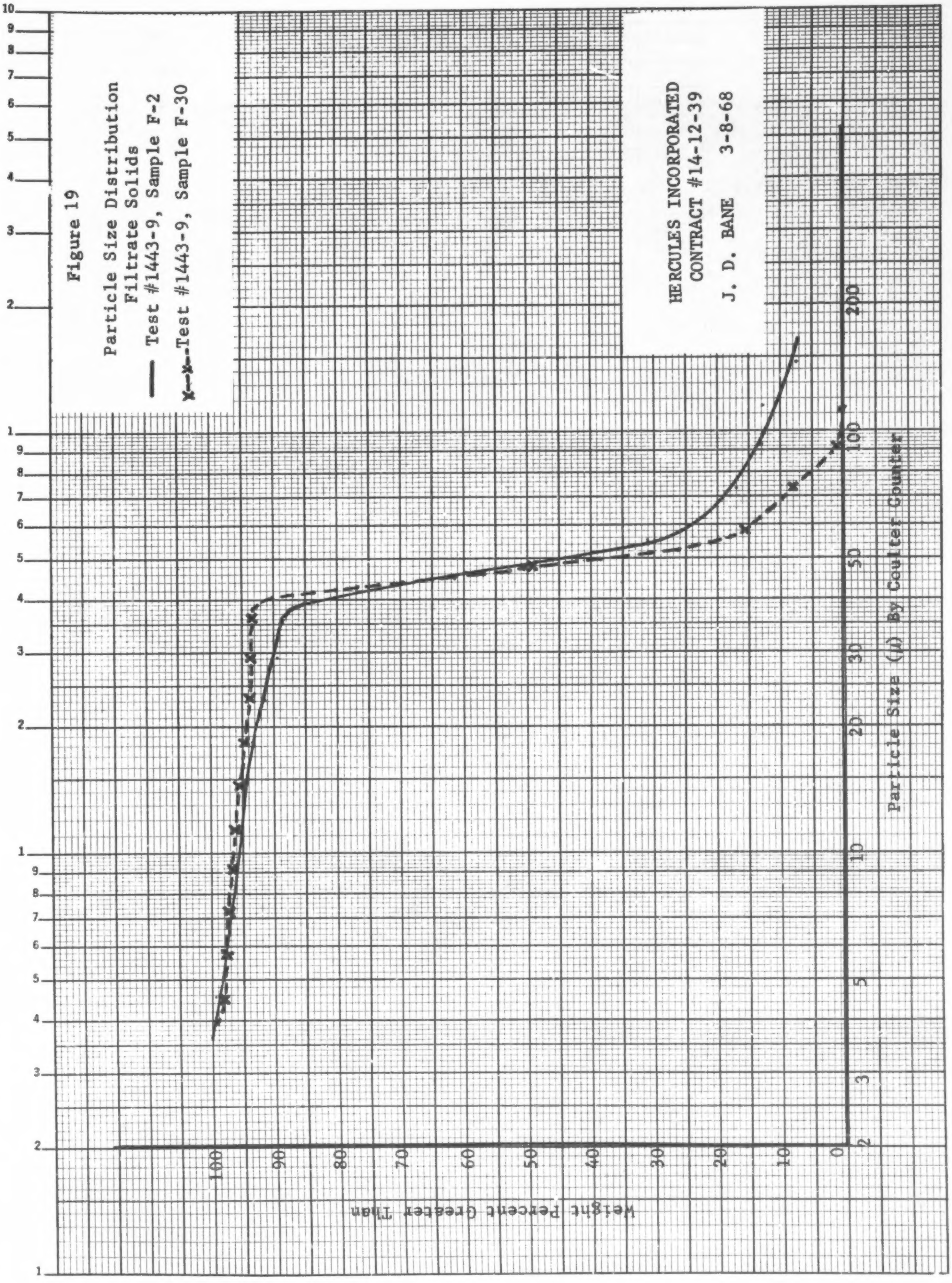


Figure 19

Particle Size Distribution
Filtrate Solids

HERCULES INCORPORATED
CONTRACT #14-12-39
J. D. BANE 3-8-68

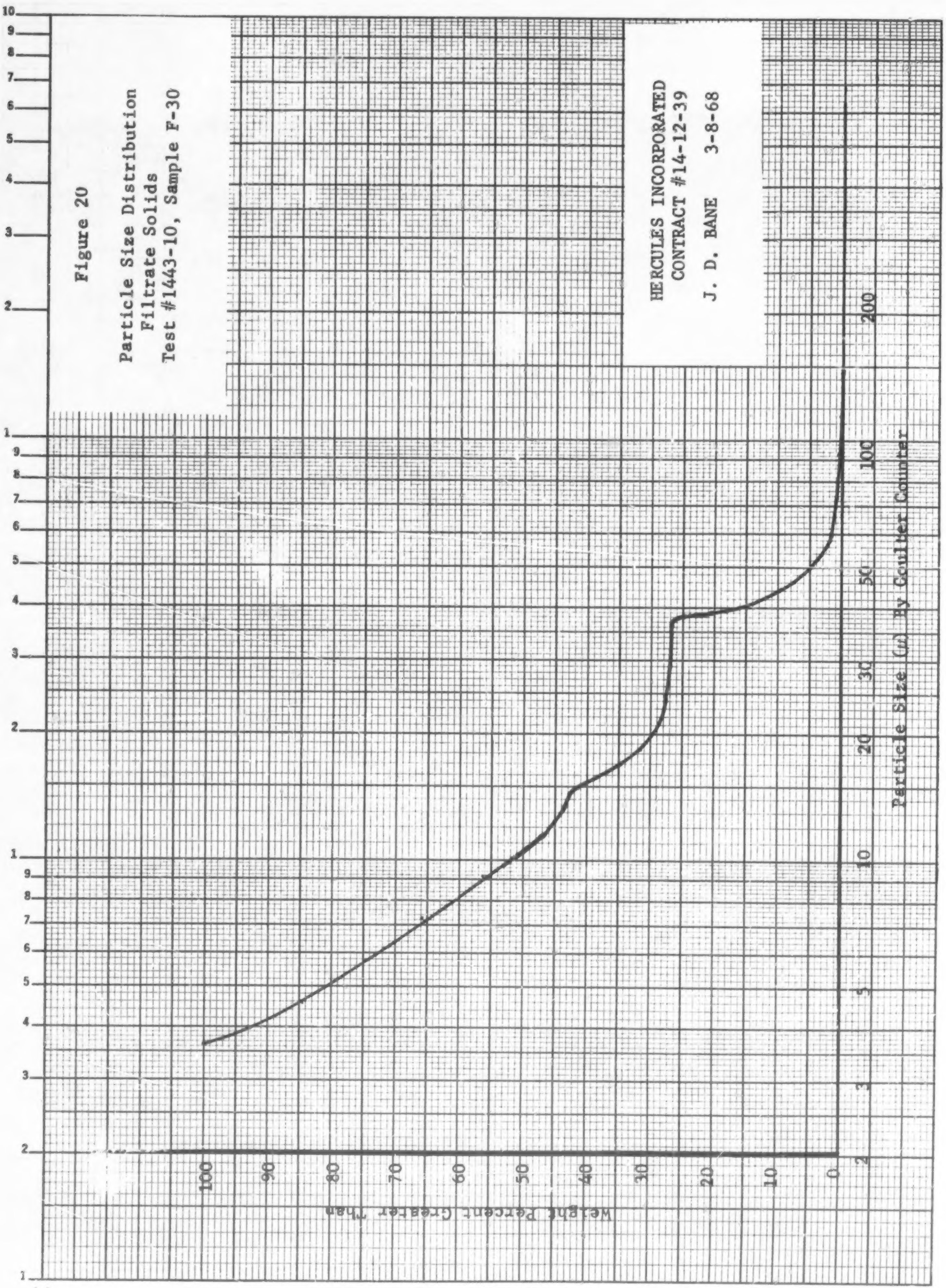


Figure 20

Particle Size Distribution
Filtrate Solids
Test #1443-10, Sample F-30

HERCULES INCORPORATED
CONTRACT #14-12-39

J. D. BANE 3-8-68

APPENDIX A

Hydrodynamics of Sewage Filtration

SUMMARY

A new concept based on the hydrodynamic approach to filtration is introduced and detailed design methods are outlined based on the analysis of the flow in the boundary layer over the filter surface and the associated forces which produce "dynamic cleaning." The feasibility of the concept is analytically demonstrated through the use of a simple but reasonable model.

CONCLUSIONS AND RECOMMENDATIONS

The hydrodynamic approach to filtration and the associated dynamic cleaning at the wall of a filter are shown to be feasible concepts. It is shown also that optimum filtration schemes are obtained when the Reynolds number of the flow is great enough to establish a thin boundary layer over the surface of the filter. In particular, conical filter geometries and particle migration concept are found to provide the best filtration schemes.

Detailed methods for analysis and design of a filter are presented with particular illustrative examples. A computer program which solves the equation of particle motion in the boundary close to the filter surface and for various geometries is the most direct approach to the design problem and, hence, is recommended. It is also recommended that the analytical study be supported by laboratory experiments to test the concepts and project these to the design of a full scale sewage plant.

INTRODUCTION

Inasmuch as the separation or collection of suspended particles appears to have been a process always known to man, filtration is often thought of as an extremely simple operation. In reality, it is not; and the practical difficulties in achieving proper filtration are numerous. Generally, the source of these difficulties is the "plugging" or "binding" of the filter medium in such a way that progressively greater pressures are needed for continued filtration. The disadvantage in high pressure driving forces lies not only in a more complex and expensive system but also in that the suspended matter is often deformable and under such pressures is compressed against the filter. The resulting closely packed cake could eventually stop the flow due to excess resistance. In order to get an idea of the magnitude of the driving force required to achieve filtration across a porous medium, the following mathematical model is often used. The formula was first obtained by Poiseuille for the laminar flow of liquids under pressure through capillary tubes. While not devised with filtration in mind, it nevertheless is widely used for flow through sand and various porous media. It is one from which many filtration equations have been derived.

A simplified form of Poiseuille's equation for smooth flow through capillary tubes is

$$Q = \frac{\pi p a^4}{8 \ell \mu} \qquad (1)$$

where p is the pressure difference at tube ends, a is the internal capillary radius, ℓ length of the opening, Q the quantity of filtrate, and μ the dynamic viscosity of the fluid. Of particular interest here is the strong dependence of the flow Q on the capillary radius. For example, by reducing to one-eighth of its size, either the pressure must be increased four thousand times to maintain the same flow or four thousand times reduction in the flow would result for the same pressure. From the point of view of filtration, the large increases in the pressure are undesirable and a substantial drop in the flow is considered a virtual "plugging".

A great variety of filtration methods are used in the chemical industry for the purpose of separating solid material from liquid or slurries. The ordinary plate-and-frame filter press working on a batch system is perhaps the most common type of filtration equipment. Rotary filters of various specialized designs, however, are used in large scale continuous processes. The essential mechanism in either case is to pump the liquid through a porous filter cloth so that the solid matter adheres to the cloth and builds up to form a "cake". The resistance through the cake is then calculated through some modification of (1) and is dependent on compressibility of the material forming the cake. If the cake is incompressible; i.e., the porosity is uniform, simple algebraic relations are obtainable for the "specific resistance" of the cake per unit thickness. Otherwise an average specific resistance is obtained from the integration with respect to "solid pressure" distribution in the cake layers.

The interdependence of the characteristics of the filter medium (i.e., the cake) and the slurry remains the key difficulty in the theoretical approach to the problem of filtration. This also explains why filtration has been developed as a practical art rather than a science. The theories have been seldom used in the actual design of a filter for a given operation. Instead they provided means for interpreting laboratory tests in seeking the optimum conditions for filtration and in predicting effects of changes in operating conditions. When examined from this point of view, it is natural, therefore, to consider the advantages that filtration would offer as it eliminates the dependence on the "cake" as a filter medium. Nevertheless a filter medium with a fixed characteristic requires continuous removal of the deposits from its surface. It is immediately clear that this approach does not eliminate the conceptual or the practical difficulties but shifts them to a new domain in technology. We are now concerned with the hydrodynamics of the particle fluid motion and seek to direct the natural forces in the flow field to promote "cleaning" at the porous wall. With this approach, the attention is focused less on the flow in the porous medium itself and more on how to achieve through changes in geometry and flow pattern the most optimum "cleaning" action. The flow conditions so determined and the knowledge of the particle size, distribution, and consistency would in turn provide information on the proper design of the filter medium itself. It is important to note that the coupling action between the characteristics of the filter medium and the flow field is thereby reduced to a conceptual difficulty and not, as before, depending on the multitude of the unknown factors which make the "cake". In what follows, we shall develop these concepts

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and examine numerous possibilities which appear pertinent in the way of achieving "self-cleaning" or even better, "dynamic cleaning."

ANALYTICAL CONSIDERATIONS

The development and formation of a hydrodynamic boundary layer over a wall, be it porous or impermeable, influences in a significant way the degree of "dynamic cleaning" that would otherwise be attained under the influence of the full momentum of the free stream. For this reason it is fruitful to examine the character of motion in the boundary layer and to review some of its features in various geometries and under laminar as well as turbulent free stream flows. The velocity distribution over a flat plate was first obtained by Blasius(1) and is shown plotted in Figure 1 as a function of η. From this, one finds that the boundary layer thickness δ is related to the local Reynolds number at a distance x from the edge of the plate by

$$\delta = \frac{5x}{\sqrt{R_{ex}}} \tag{2}$$

where $R_{ex} = (\rho\, u_\infty\, x)/\mu$. For instance, at a distance x = 10 cm from the leading edge, δ is of the order of one half of a millimeter. For the flow over a porous wall there is no similar general solution. Thus, under the assumption that asymptolically $\frac{\partial u}{\partial x} = 0$, it is obtained

$$\frac{u(y)}{u_\infty} = \left(1 - e\right)^{v_o y/\nu} \tag{3}$$

where v_o is the constant discharge velocity. The practical restriction on (3) is the requirement of small v_o, namely $0.0001 < v_o/u_\infty < 0.01$. From (3) one can readily obtain the expression for displacement or momentum thickness; i.e.,

$$\delta^* = \frac{\nu}{-v_o} \tag{4}$$

$$\theta = \frac{1}{2}\frac{\nu}{-v_o} \tag{5}$$

The velocity distribution is seen plotted in Figure 2, Curve I. Curve II, drawn for the purpose of comparison, represents the boundary layer without suction. It should be noted that the suction profile is fuller in this case.

Other solutions of the boundary layer are known for flow patterns which can be associated with similar velocity profiles. Examples of such solutions are obtained over a flat plate with a suction or blowing velocity v_o proportional to $1/\sqrt{x}$ and in a convergent channel with v_o proportional to $1/x$. The solutions of the velocity profile over a flat plate are shown plotted in Figure 3a and those in a convergent channel in Figure 3b. In these figures, the positive values refer to suction and negative to blowing at the boundary. The decrease in the boundary layer thickness with suction and increase with blowing should be noted. The phenomenon implies a greater sensitivity of the boundary layer thickness to blowing than to suction. With the application in mind of these findings to filtration, one can expect "flashing" or backwashing of the filter wall through a process of blowing. In Figure 3c the profiles in a convergent channel and over a flat plate are shown compared for v_o = o and the former is found to be much fuller.

It is known(1) that the development of the boundary layer in the entrance region of a channel or a pipe flow at high Reynolds number is identical to that over a flat plate. Different problems, however, evolve when the Reynolds number is not large.

This problem has been treated(5) as a perturbation to Poiseuille's flow and solutions were obtained for very small discharge (suction). It is found that the velocity profile in the major flow direction deviates from the Poiseuille parabola by being flatter at the center of the channel and steeper in the region close to the walls, the degree of deviation depending on the Reynolds number for the flow through the channel walls (i.e., v_0h/ν). Solutions exist for a straight channel with impermeable walls(6) for Reynolds numbers up to 500. A surprising result of this analysis is that the velocity profile for small entrance distances is not convex, see Figure 4. It possesses a local minimum on the axis $y = 0$ and symmetrically situated maxima on either side of it.

The velocity distribution in the entrance region of a pipe may be affected to a considerable degree if all or part of the wall is porous. When all the wall is porous and there is a total absorption, a stream line pattern such as shown in Figure 5 is obtained.(7) A careful study of the latter case has been made recently.(8) The streamlines for a total absorption from this analysis are shown in Figure 6a. The absorbing wall is located along the entrance length equal to 20% of the pipe radius. We note the bounding streamline which meets at the downstream edge of the absorbing wall, runs along the axis of the pipe to a stagnation point beyond this edge, and from there fans out as a surface of revolution towards the walls. Beyond this surface are circulations which produce a return flow along the axis.

More details about the velocity distribution are given in reference 8. The results for a Reynolds number of 40 are shown plotted in Figure 6b. It

It has been shown before that in the absence of absorption the initial velocity profiles are not convex but have a local minimum on the axis and symmetrically placed maxima on either side. However, we see here that the effect of absorption is to draw out the velocity profile and so straighten off the concave region.

Turbulent Boundary Layer

Transition into turbulent boundary layer may occur if the Reynolds number R_{ex} exceeds a critical value. The critical Reynolds number over a flat plate is found to be between 3×10^6 to 4×10^6 and is somewhat smaller if the free stream is also turbulent. A similar trend is also expected with a rough surface. The presence of a pressure gradient in the external flow has a strong effect on the boundary layer transition. Accelerated flows ($dp/dx < 0$, $d\bar{u}/d_x > 0$) favorable pressure gradient) are considerably more stable than decelerated flows ($d_p/d_x > 0$ $d\bar{u}/d_x < 0$, adverse pressure gradient). When there is a suction at the boundary, it is shown$^{(1)}$ that critical Reynolds number increases over one hundred times its value with no suction.

In a turbulent flow past a smooth boundary we may distinguish among three regions$^{(9)}$: (1) adjacent to the wall, an extremely thin region where the flow is predominantly viscous (this is called the laminar sublayer and its thickness is designated by δ_ℓ), (2) an intermediate buffer layer where the flow is turbulent but directly influenced by viscosity, and (3) the rest of the flow region where the direct viscous effects are negligibly small.

It is interesting to note that even with a perfectly smooth wall the thickness of the viscous sublayer is of the order of .001 to .01δ and that the mean velocity in this region increases linearly with the distance from the wall. For the velocity distribution in the buffer zone, a simplified picture of the flow is obtained in which the velocity distribution is often expressed by a power law. Similar approximations are obtained for the velocity distribution in a pipe as seen in Figure 7. In the same figure is also seen plotted the velocity profile in a fully developed laminar pipe flow. From the comparison of the two curves one obtains an idea of the extent of the momentum penetration into the boundary layer and close to the wall of the pipe. In the laminar flow, the entire flow field is a "boundary layer" whereas in a turbulent flow the boundary layer is thin indeed. The two dotted curves plotted in this figure are obtained from the boundary layer analysis at the extreme region to the pipe, x/2a designating the proper location. The layer thickness gradually increases along the pipe until it approaches the fully developed profile at large distances downstream.

Experimental measurements of the boundary layer thickness over the walls of a converging channel yield values much smaller than that over a flat plate. The velocity profile obtained from such measurements is shown plotted in Figure 8. In that figure u/u_m is plotted against the distance from the centerline for the convergence angles shown and may be directly compared with that in a turbulent pipe flow. The latter is designated by a zero convergence angle. Again, it is seen that a considerable reduction in the boundary layer thickness is obtained through a simple change in the flow geometry. This result has a direct bearing on the dynamic cleaning in filtration.

Completely new problems present themselves when the motion of the suspended matter is also considered. This problem will be taken up next.

Dynamics of a Two-Phase Flow

Ideally, one should discuss at this point such related topics as the size, distribution, concentration, and consistency of the pollutants; i.e., the "particles" in a sewage. However, the detailed consideration of such matters will take us right outside the scope of the present work. It suffices to note that the total solid content of the sewage is of the order of .1%, sizes range from one to several hundred microns and the consistency of the suspension is mostly organic matter. There are found sand particles, hair, lint, oil and a multitude of other varieties of suspended matter in a sewage effluent. Naturally an exact analytical treatment of a problem of this complexity is not practical. An order of magnitude analysis of the problem relevant to "dynamic cleaning" may be attempted, however, without too much complication if we assume that the suspensions have regular geometric forms, such as small rods or spheres. A sphere moving through a very viscous liquid with velocity, w, relative to a uniform simple shear experiencesa lift force(10)

$$L \simeq 81.2\mu\, wa^2\, k^{1/2}/\nu^{1/2} \qquad (6)$$

perpendicular to the flow direction. Here, a denotes the radius of the sphere, and k the magnitude of the velocity gradient. Under restrictive conditions, the above result was applied to the motion of a sphere in a Poiseuille flow through a pipe simply by calculating the relevant velocity gradient and substituting for k in (6). It was shown in reference (10) that the direction of the sidewise force is toward the center of the pipe when the particle lags the fluid, and away from the center and towards the wall when the particle leads the motion of the fluid. Stated in an equivalent way, the down motion of a heavy particle causes it to drift toward the wall but the same motion of a neutral or light particle causes it to migrate toward the center. Since we are interested mainly in the region of the flow close to the wall, the use of (6) requires some justification. It turns out that for a very small particle, one can make the Reynolds number based on the velocity gradient $R_{e_k} = ka^2/\nu$, very small compared to unity. In a boundary layer region this value is reduced even further if $(a/x)^{1/2}$ is also small. In other words, despite the presence of the wall, very small particles do not feel its presence and (6) may still be applicable. With due regard to stated technical difficulties we venture to employ (6) to examine the magnitude of the side force developed at a point not too far away from the wall in a Poiseuille flow and compare it with that obtained in a boundary layer over a surface with absorption. Such comparison yields a lift force (25u) times greater than that in a Poiseuille flow. It may be said, therefore, that the effect of boundary layer is to promote cleaning in two ways - one due to deeper penetration of the flow momentum close to the wall, and the other - development of a useful side force on a particle.

The presence of the above sidewise force on a solid as well as deformable particles have been experimentally confirmed by many investigators. The apparatus used in most of these experiments was limited to capillary tubes in the order of 1 cm and particles were close to neutral density having dimensions in the order of several hundred microns. The first to show this phenomenon was the experiments of Segre and Silberberg(11) who demonstrated that a rigid sphere transported along in Poiseuille's flow through a tube is subject to radial forces which tend to carry it to a certain equilibrium position at about 0.6 tube radii from the axis irrespective of the radial position at which the sphere first entered the tube. A typical particle count distribution and density histogram are shown in Figure 9. The reader is referred to reference(11)for the details of experimentation and data reduction. Experiments(12) on deformable liquid drops and tiny threads (which undergo shear deformation) show that these also migrate toward the tube axis. Later experiments(13) showed that dense particles falling slowly through an upward moving fluid migrate to the tube axis; buoyant particles in the same flow migrate to the tube walls. More experimental data are presented in reference (14) wherein the effects of initial particle concentration and entry length on the migration of neutral density spheres from the wall are carefully reported. It is noted in that reference that the region outside the concentration peak always consists of a particle-free layer of suspended fluid indicating that the particles making up the concentration peak probably come from this region. The height of the wall peak is shown to increase with the distance from the entrance to the tube according to the plot seen in Figure 10. The ordinate in Figure 11 is the plot of the relative peak $(N_h)_{max}$ to trough $(N_h)_{min}$ particle counts. At the same tube location, the wall peak is shown in Figure 11 to decrease rapidly with small concentration and then level off. From these results it would appear that, while the initial creation of the peak takes place somewhere in the region of the mouth of the tube, it continues to develop during the passage down the flow tube. This gradual increase in the height of the peak is accompanied by a narrowing of the peak which is caused by the passage of the particle into this region from faster moving streamlines. In earlier experiments(12) measurements at 350 pipe diameter downstream of the inlet detected no particle migration, however. It is furthermore demonstrated in reference (14) that the wall peak is a function of the initial concentration. The possible reason for this is a particle-particle interation at high concentration.

The Criterion for Design of a Filter

In the foregoing discussion we have considered filtration from the hydrodynamic point of view in the sense that the characteristics of the filter medium may be uncoupled from those of the suspension provided caking is prevented at the filter wall. We also devoted particular attention to the character of the flow in the vicinity of the wall under a variety of flow conditions. We found that favorable flow conditions could be developed at the wall in both turbulent and laminar flow. Under these conditions the momentum of the fluid is made to penetrate deeper into the boundary layer and close to the wall. This way the viscous flow is limited to an extremely thin region next to the wall and the predominant portion of the flow field is thus imparted with inertial forces transporting and imparting energy to the suspended matter in the field. It was pointed out very clearly that the thin boundary layer not only limits the portion of the slow moving fluid particles in the field to a minimum but it also sets up a strong velocity gradient at the wall which acts to deflect the approaching particles from the boundary. It is the purpose of this present section to develop a better understanding of this mechanism and perhaps a confidence that it does indeed apply to filtration in a practical sense. In the way of developing the ideas, we arrive at the criteria which are so germain to the actual design of a filter. Naturally, our results will be severely limited for two reasons: (1)to keep clarity of presentation we examine only the most simple model, and (2) the full description of the flow field, even if possible, is not available at the present time. Nevertheless, we shall demonstrate for the selected model the feasibility of the concept as a mathematical tool to arrive at a meaningful design of filters.

The schematic of a model to be considered is shown in Figure 12a. Mathematically, the flow may be that over a flat plate and physically the plate may be thought of as a part of the entrance to a channel. We assume that the Reynolds number of the flow is great enough to allow development of the boundary layer ($R_{ex} = 2 \times 10^5$, say). We furthermore assume that there is a uniform discharge through the filter wall with an effective constant velocity v_o. To keep the analysis simple, we consider only the assymptotic flow condition represented by the simplified equation (3). Unfortunately, the consequence of this choice is a small v_o, that is small in terms of filtration requirements. We shall return to the discussion of this matter later. Meanwhile, letus emphasize that while different problems arise when there is a total absorption at the wall, the effect of the thin layer and the associated particle migration remain valid. Only the physical arrangement of the filtration system may undergo a suitable change with the requirements for dynamic cleaning. Returning now to Figure 12a, we identify the following: the edge of the boundary layer, the velocity vector tangent to the streamline at a region just outside the boundary layer and the longitudinal velocity profile inside the layer. We note that the latter drops from its maximum value at the free stream to zero at the wall, whereas the relative magnitude of v_0 with respect to u progressively increases. The predominance of the velocity component towards the wall over that along it would direct the resultant velocity vector more and more towards the wall until it eventually becomes perpendicular to it. Meanwhile, there are two types of forces acting on a particle which is trapped in this region - one is a drag force directed along the resultant velocity vector whose magnitude is given by $6 \pi \mu w a$ and the other is a lift force perpendicular to the first and its magnitude is estimated by (6).

Now, consider again the point just outside the boundary layer in Figure 12a. The corresponding force diagram acting on a particle at this point is sketched in Figure 12b. Thus the underlying thought in the proper design is to arrive at a resultant force on the particle acting away from or at most parallel to the wall before the particle is too close to the wall. It turns out that for a given flow condition progressively smaller particles approach the filter wall as they penetrate the boundary layer. The larger particles are being deflected away due to the strong lift producing forces and relatively small drag. From the geometry of the streamlines, it is seen that whenever the drag and lift forces are equal, the resultant force is parallel to the wall. The maximum particle sizes for which this condition prevails at the wall determine the criterion for the design of the filter. Clearly, the particles below this size must be allowed to pass through the filter without appreciably changing the filter resistance, otherwise a cake may form on the filter wall. Now, let us return to the mechanics of determining this particle size for the problem under consideration.

The ratio of lift to drag forces is obtained from dividing equation (6) by the drag 6 $\pi \mu$ a w; i.e.,

$$\frac{L}{D} = 4.32 \frac{a}{\nu^{1/2}} \left(\frac{du}{dy}\right)^{1/2} \qquad (7)$$

The expression for the velocity gradient is available from a direct differentiation of (3), namely,

$$\frac{du}{dy} = \frac{u_\infty}{\delta^*} e^{-y/\delta^*} \qquad (8)$$

Substitutions of (8) into (7) and some algebra yields the basic design equation

$$\frac{L}{D} \simeq 200 \frac{d}{\delta^*} e^{-y/2\delta^*} \qquad (9)$$

There is a particular equation applicable only to the problem under consideration. In its derivation we assumed as stated earlier that $R_{e_x} = 2 \times 10^5$. Also, we made use of the approximate relations $R_{e_\delta} = 5.5(R_{e_x})^{1/2} = \frac{R_{e\delta^*}}{.34}$ which were obtained from (12).

Equation (9) states that the lift to drag ratio for a particle which is (d/δ^*) times smaller than the displacement thickness varies exponentially with the distance y from the wall, reaching its maximum value at the wall and vanishes outside the boundary layer. A significant restriction on (9) is for (d/δ^*) to be much smaller than unity. This is the condition for which (7) is most likely to apply. Consider now the following tabulated data obtained from evaluating (9) for the three (d/δ*) shown in Table II.

TABLE II

LIFT-TO-DRAG RATIO

y/δ	L/D		
	d/δ*=1/200	d/δ*=1/100	d/δ*=1/20
0	1.00	2.000	10.00
.5	.7788	1.5576	7.788
1.	.6065	1.2130	6.065
1.5	.4724	.9448	4.724
2	.3679	.7358	3.679
3	.2231	.4462	2.231
4	.1353	.2706	1.353

The values on the top right hand side of this table are indicative of the conditions wherein most likely dynamic cleaning would prevail. The column for the particle size 1/200 shows that such particles reach the wall but they probably slide over it. The particles of the size 1/100 are deflected at a distance as close as δ* units from the wall. Once they are past this distance they probably contribute to build up of a cake unless they are absorbed by the filter.

The presentation in this section shows that under certain flow conditions it would become possible to direct the forces in the fluid field to attain dynamic cleaning. We purposely avoided complications in the attempt to demonstrate conceptual feasibility. Whether or not such conditions are reasonably obtained under actual circumstances requires careful experimentation.

We have already examined the detrimental effect of the total absorption in Figure 6. In this example only the upper part of the pipe has a porous wall. The pattern of the streamline shows a large stagnation region and some inverse flowing streamlines. The latter would bring to the porous wall some suspensions from the central region of the pipe and accumulate them at the wall. Thus for a good cleaning action the pattern of the stream lines should be as straight as possible along the channel but undergo a rapid curvature at a distance as close to the wall as possible. This pattern of streamline cannot be obtained with total absorption. It is necessary that a portion of the fluid leaves the pipe to avoid the build up of a stagnation region. The presence of this region causes the reverse flow of the streamlines which is so detrimental to the dynamic cleaning. The change in the geometry of the channel would contribute to decreasing some of these effects in a total absorption. A combined advantage of a suitable geometry and flow Reynolds number would probably make a close to total absorption possible.

A quick review of Figures 1 through 8 brings us rapidly to the point we wish to make with respect to the choice of flow geometry. Throughout this review we must keep in mind: (1) energy is expended to move the fluid through conduit, and (2) an efficient transport of the suspended matter requires a uniform distribution of this energy across the conduit. This implies that viscous dissipation of energy must be limited to as thin a region as possible at the wall. Now, it is obvious that a parabolic distribution such as obtained in a fully developed pipe or channel flow (Figure 5) is the least effective scheme from the above point of view. On the other hand, the fully developed turbulent flow in a pipe (Figure 7) shows a substantial improvement over the laminar flow. Note the penetration of the high velocities close to the wall and into the boundary layer. The velocity profile in a convergent channel or in a cone, be it for a laminar or turbulent flow, is more uniform than the corresponding flow in a straight channel or a circular pipe. Naturally, the turbulent flow in a channel (Figure 8) has the most suitable velocity profile. Note, however, that to obtain a turbulent flow, a penalty has to be paid in terms of excess energy. For this reason, we look into the boundary layer formation, first over a flat plate (Figure 1) and then in the entrance region to a channel (Figure 4) and we note a boundary layer is almost established at this region at considerably lower Reynolds numbers.

In a second proposed filtration scheme wherein energy is imparted to the fluid but in a much lower level, one can make use of the particle migration phenomenon (Figure 9). Since the particles are naturally concentrated in a ring away from the wall, one can profitably consider a filtration system suggested by the sketch in Figure 13. There are shown two concentric pipes. The inner pipe is impermeable throughout its length. The outer pipe is made impermeable only along a suitable length at its lower end. Only this part envelops the inner tube. The major filtration process occurs in the annulus and through the wall of the outer pipe. The flow is allowed to develop in the outer pipe to a point where the greatest concentration distribution of the suspended matter is expected. At a point along this pipe where the "necklace" effect is best developed, the segment of the porous wall begins. Close to this point the inner tube should also begin. The diameter of the inner tube should be so chosen that only the most dilute suspension is allowed to pass into the annulus region. Provision should be made not to disturb the distribution of the suspended matter. Presumably, then the most concentrated matter follows into the inner pipe. This fluid may be collected and recirculated to obtain a further increase in the concentration using the same loop or equivalent to it. The excess deposit in the annulus may be periodically flushed out and recirculated. The necklace phenomenon is not reported in very large pipes, however, In practice, there is a certain trade-off of various parameters. A fully developed flow establishes itself after a long distance (over 50 diameters) downstream of the entrance region. From this point of view, there is an advantage in using smaller diameter pipes as physical pipe length will be correspondingly shorter and filter units would be easier to handle. For example, replaceable filter modules could be made which are occasionally taken out and inserted in a fresh water cleaning circuit. In principle, the scheme suggested here operates on the concept of total absorption which takes place in the annulus. The difficulties are reduced in here because of the diluted concentration and allowance for some particle deposition which is flushed out in a later cleaning process.

In an earlier discussion we have made a reference to the process of blowing fluid into the boundary layer through the wall. It was shown (Figure 3) the thickness of the layer increases appreciably with a relatively small amount of blowing. The thickening of the boundary layer could be used with advantage in backwashing the walls of a filter. By means of an intermittent blowing and rapid circulation of a clean fluid in the pipe, one can induce a corresponding oscillation in the fluid near the wall and the eventual removing of a build-up of deposits.

LIST OF SYMBOLS

Q - quantity of flow

a - radius of a pipe or sphere

P - pressure

μ - dynamic viscosity

u - fluid velocity

ρ - density

x - coordinate (usually longitudinal or the distance from the leading edge of a flat plate and/or inlet of a pipe)

t - time

y - coordinate in the transverse direction

u_m - maximum velocity

u_o - initial velocity

u_∞ - free stream velocity

ν - kinematic viscosity

δ - boundary layer thickness

δ^* - displacement thickness

θ - momentum thickness

δ_ℓ - laminar sublayer thickness

R_e - Reynolds number depending on u, u_m, $\overline{u}$ or u_o or v_o

v_o - suction velocity at the wall

$\overline{u}$ - average velocity

v - transverse velocity

η - $y\sqrt{u_\infty/\nu_x}$

λ - y/h

h, b - channel half-width

w - relative velocity of a particle

D, F - drag force

L - lift force

k - velocity gradient

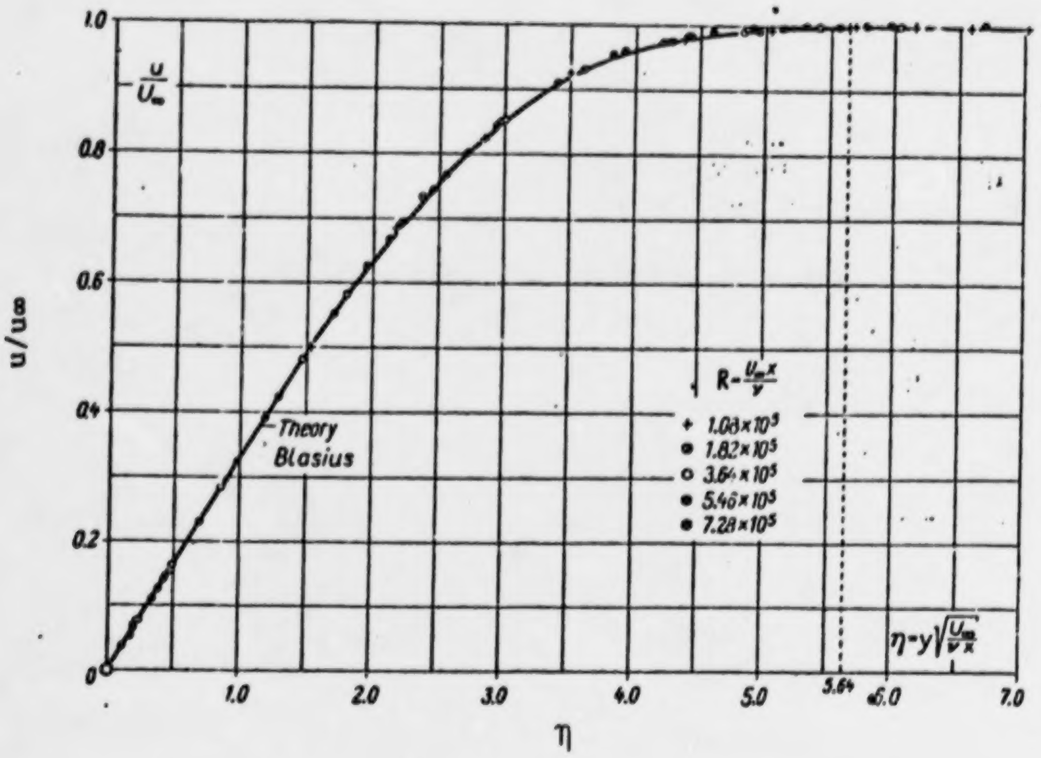

Figure 1. Velocity Profile in the Laminar Boundary Layer Over a Flat Plate

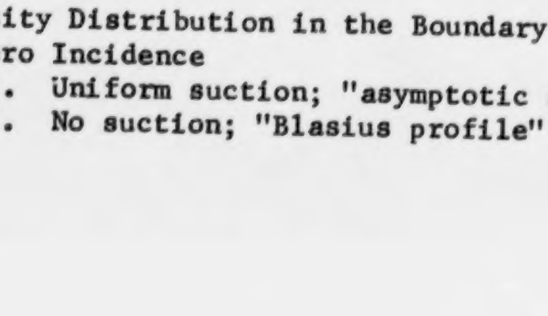

Figure 2. Velocity Distribution in the Boundary Layer on a Flat Plate at Zero Incidence
I. Uniform suction; "asymptotic suction profile"
II. No suction; "Blasius profile"

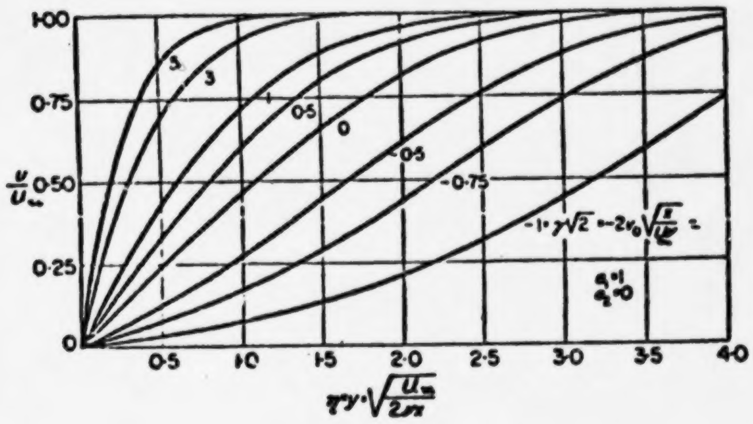

Figure 3a. Velocity Profiles in the Boundary Layer on a Flat Plate with a Suction Velocity Distribution $v_o \sim 1/\sqrt{(x)}$. (Reference 4)

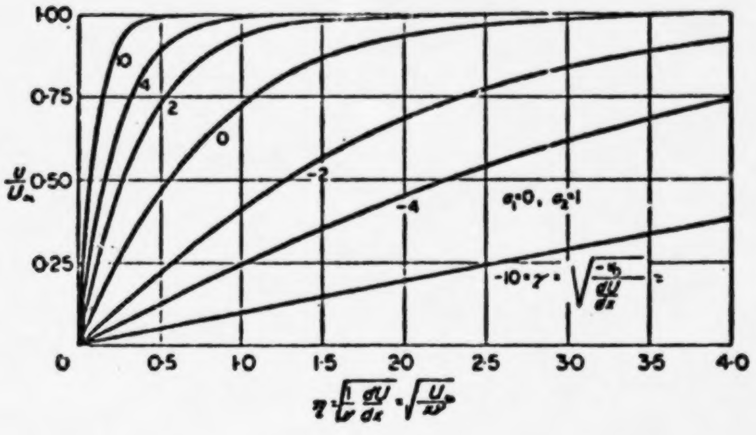

Figure 3b. Velocity Profiles in the Boundary Layer of a Convergent Channel (Sink Flow) with a Suction or Blowing Velocity $v_o \sim 1/x$. (Reference 4)

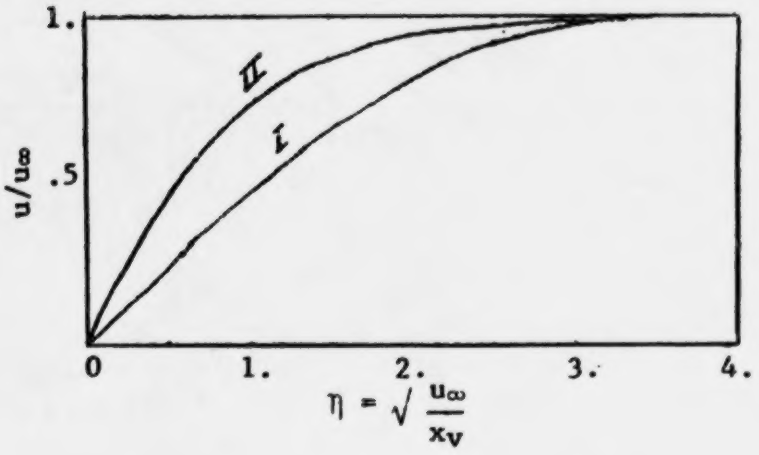

Figure 3c. Comparison of Velocity Profile for a Flat Plate (I) with That in a Convergent Channel (II)

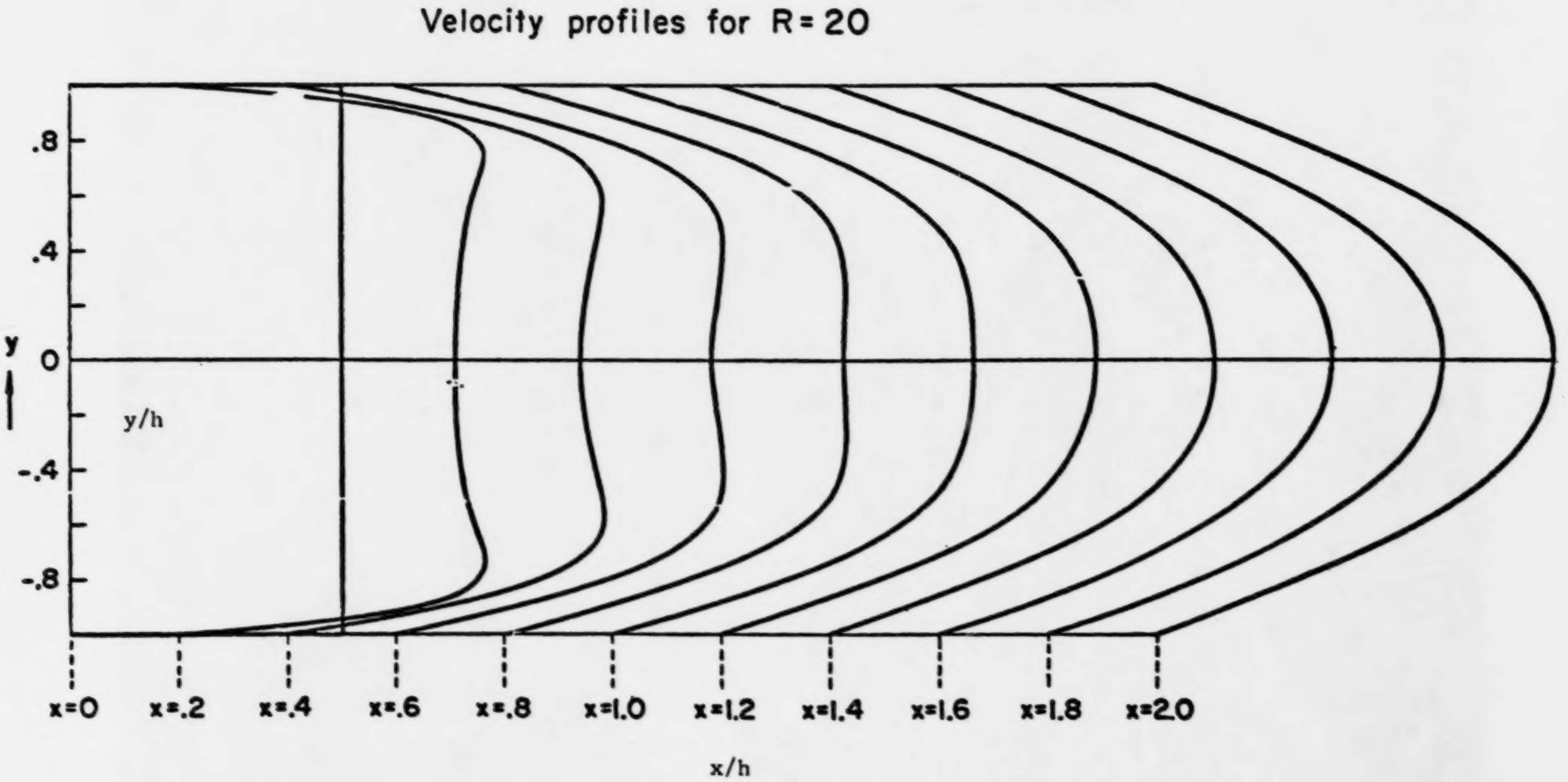

Figure 4. Development of Velocity Profile in a Channel (Figure 10b)

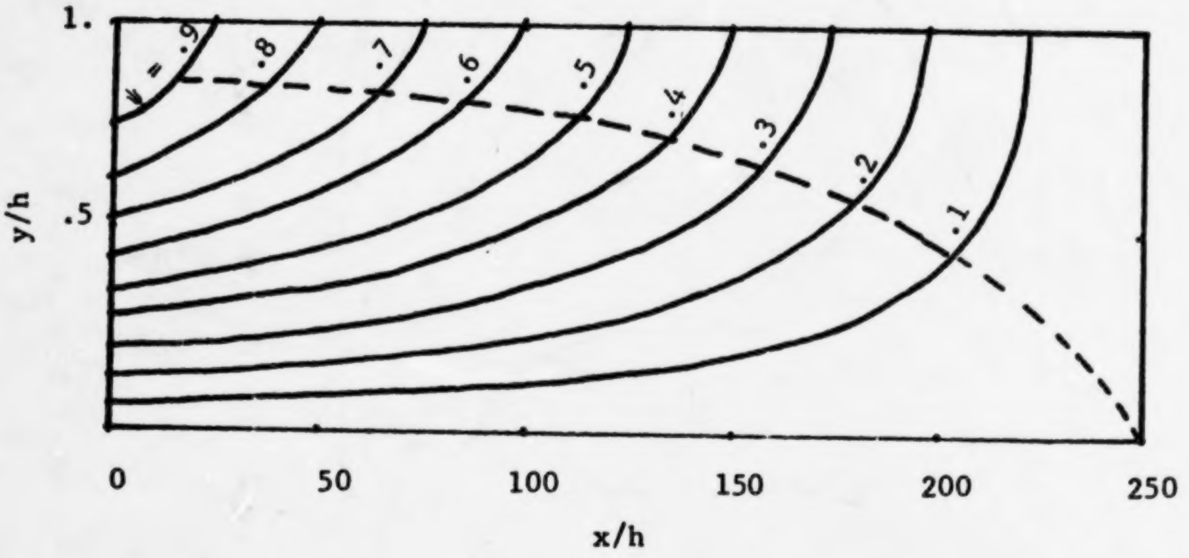

Figure 5. Streamline Pattern in a Total Absorption

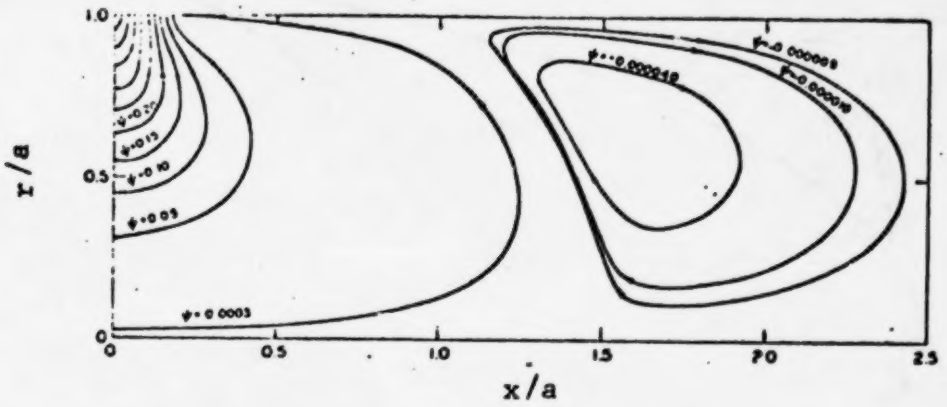

Figure 6a. Streamlines in the Case of Total Absorption $R_e = 0$

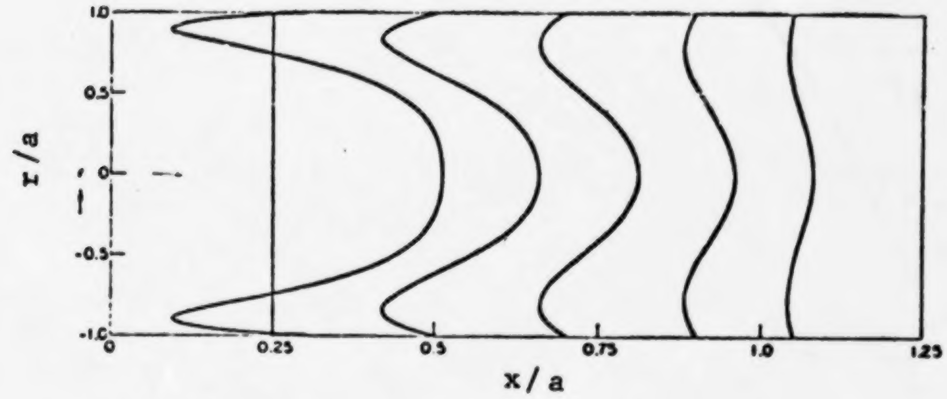

Figure 6b. Velocity Profile at the Extreme Region of a Pipe, $R_e = 40$, $\frac{v_o}{\overline{u}} = 2.5$

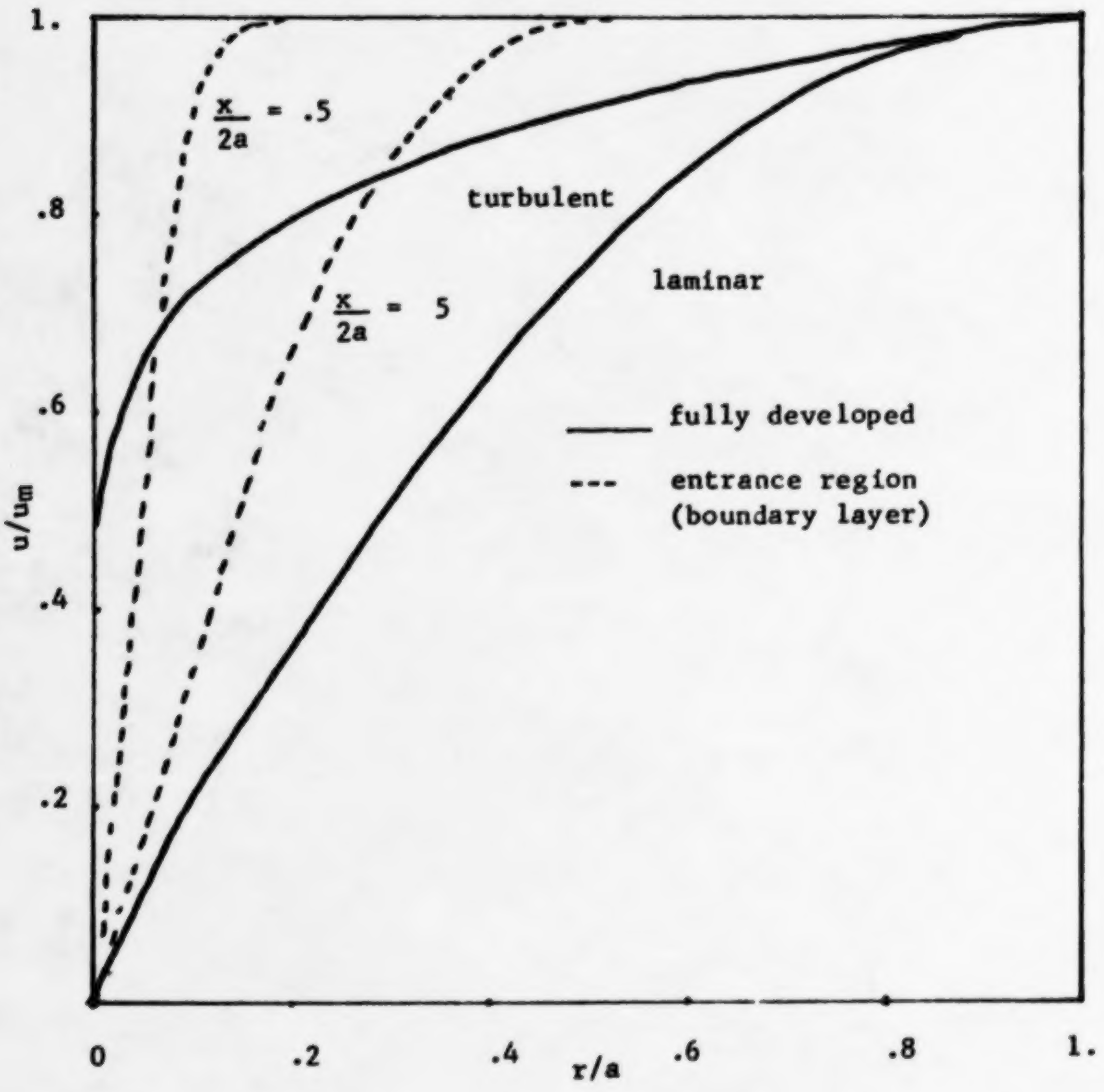

Figure 7. Comparative Study of the Fully Developed Velocity Profile in a Pipe with Boundary Layer in the Entrance Region

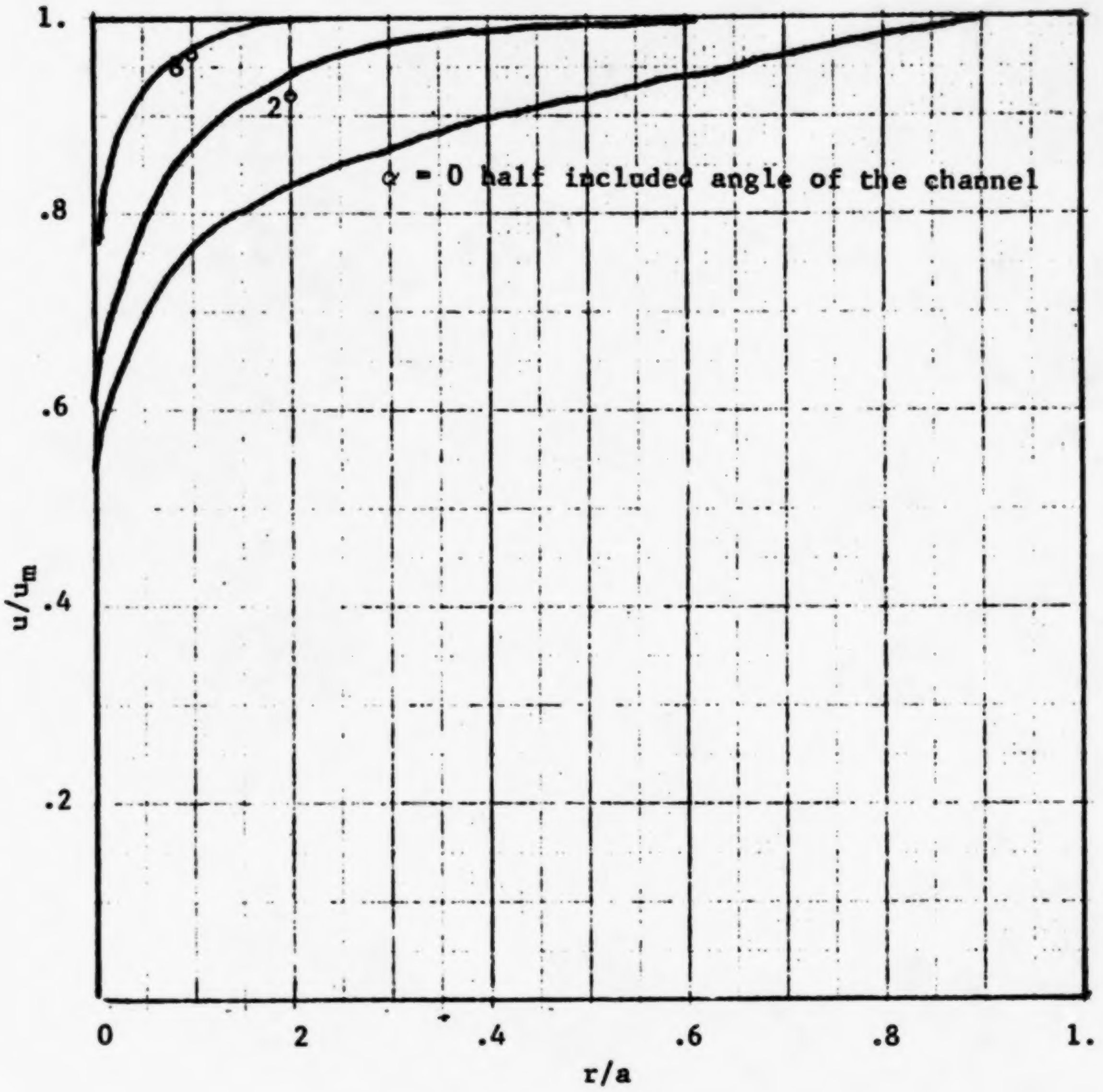

Figure 8. Turbulent Profile in a Convergent Channel

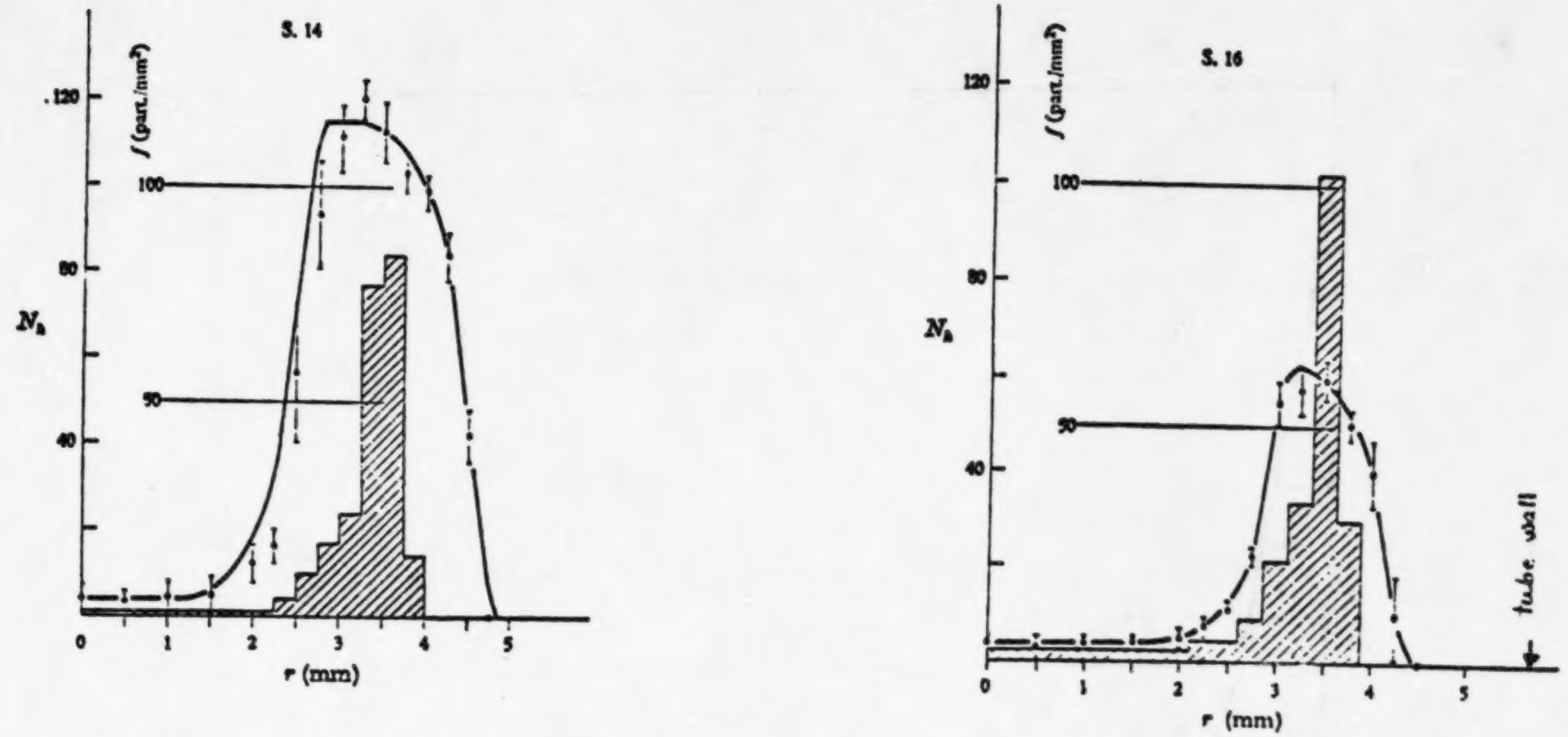

Figure 9. Derived hit coincidence count N_h and hit density f for series S.14 and S.16; dependence on radial position r. (For data in case S.14, see Table I. S16 has been performed under the same conditions but with smaller Δx.) Standard errors in N_h are indicated. Full lines reconstructed from f.

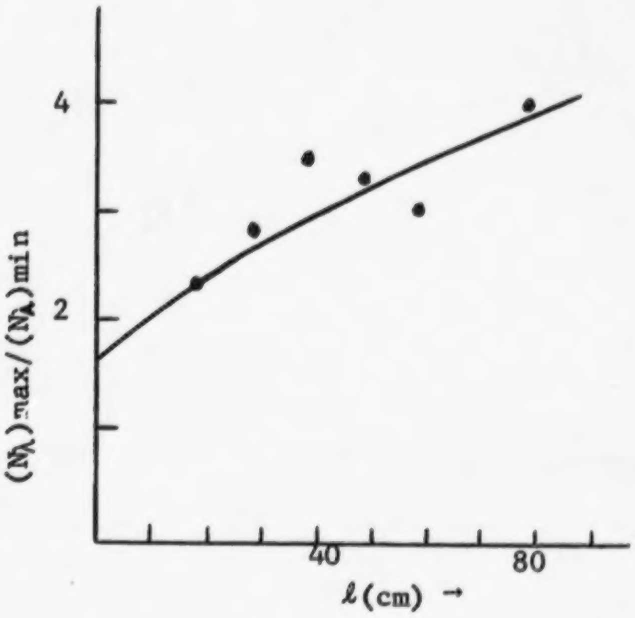

Figure 10. Variation of Height of the Wall Peak Along the Length of the Flow Tube at C = 2.90 particle/cm^3, R_e = 540

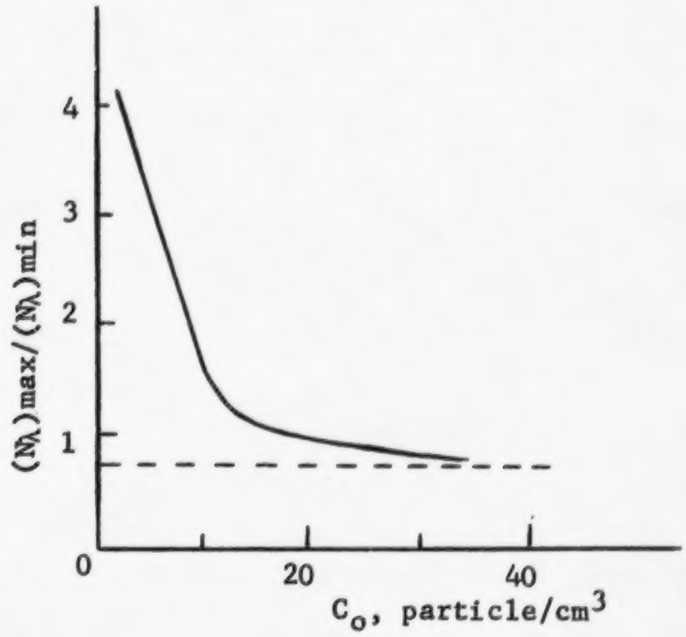

Figure 11. Variation of Height of the Wall Peak with Concentration

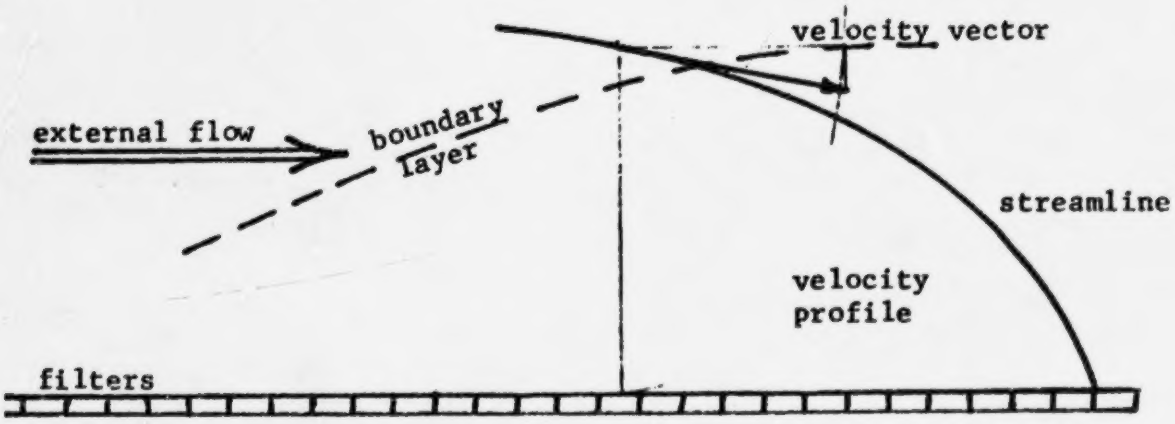
velocity vector
external flow
boundary layer
streamline
velocity profile
filters

Figure 12a. Boundary Layer Velocity and Streamline Diagram

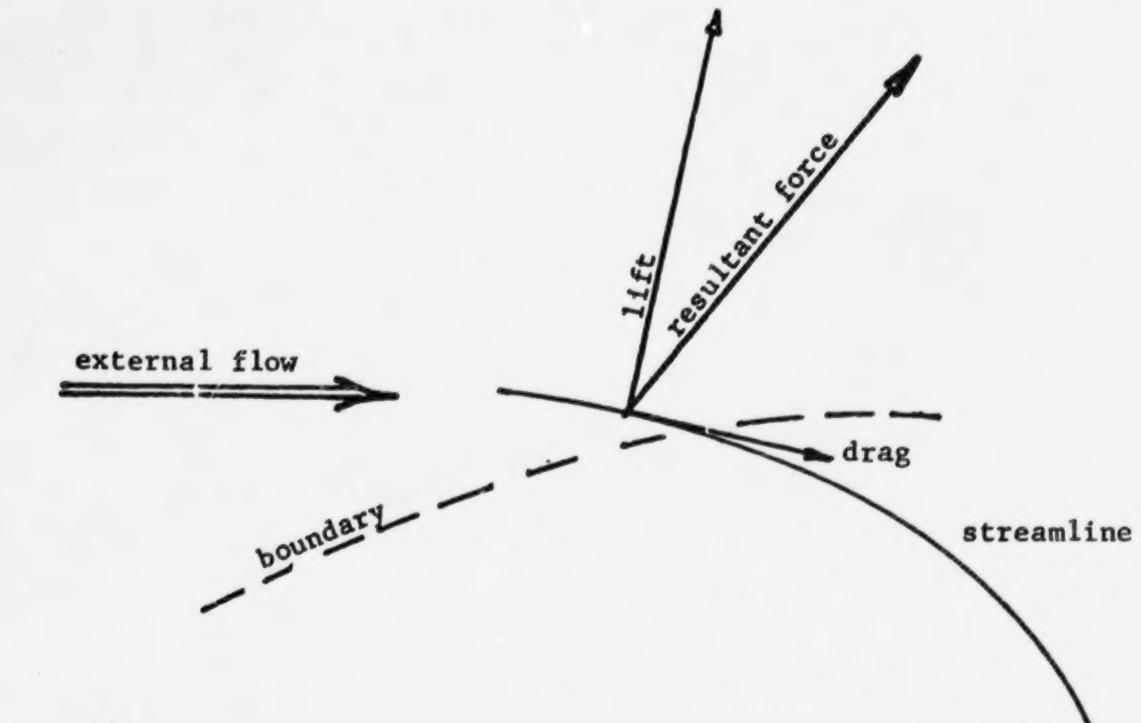
lift
resultant force
external flow
drag
boundary
streamline
filter

Figure 12b. Force Diagram

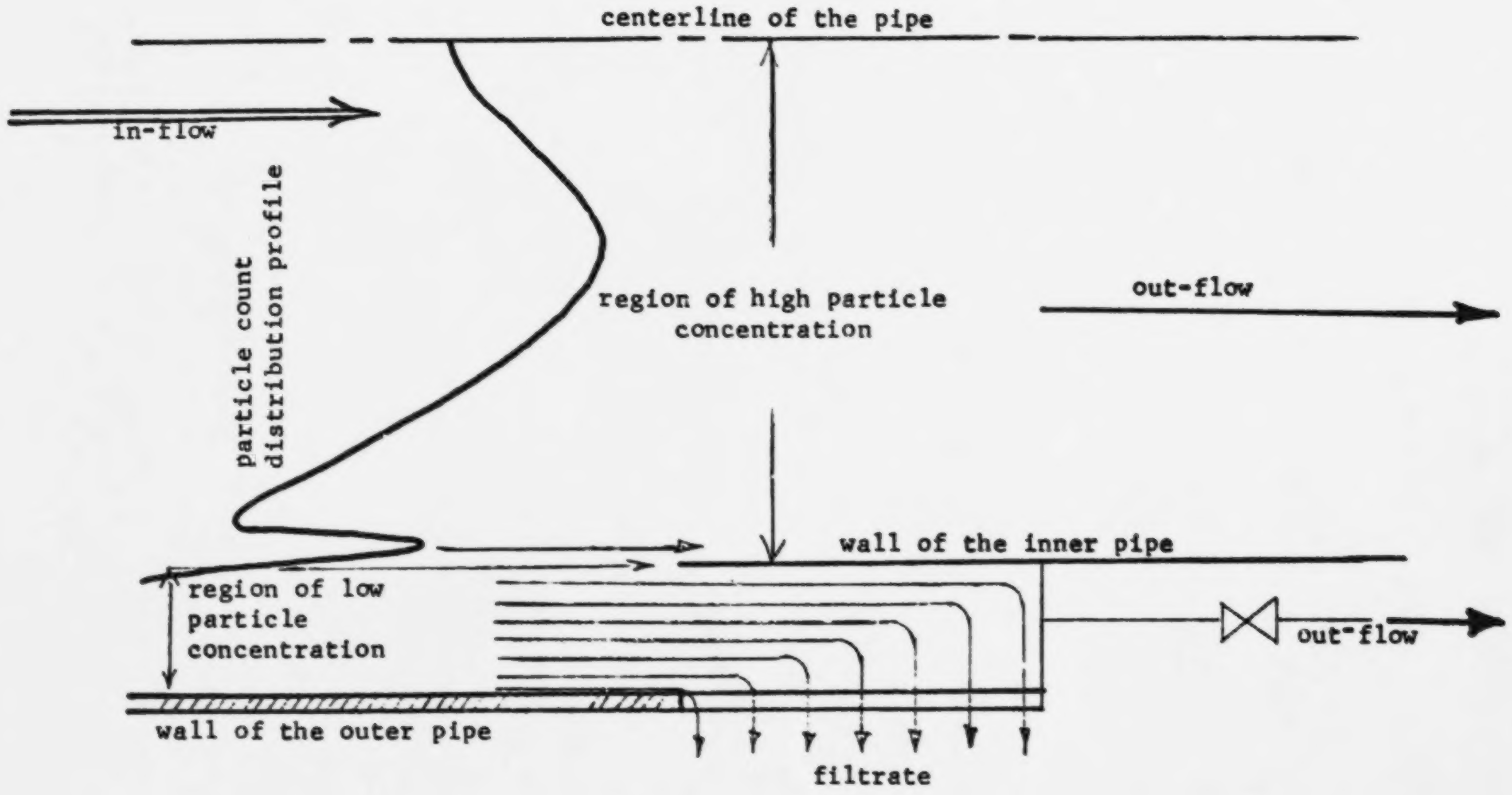
centerline of the pipe
in-flow
particle count distribution profile
region of high particle concentration
out-flow
wall of the inner pipe
region of low particle concentration
out-flow
wall of the outer pipe
filtrate

Figure 13. Filtration Using Particle Migration Phenomenon

REFERENCES

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(13) Jeffrey, R. C., and Pearson, J. R. A., "Particle Motion in Vertical Laminar Tube Flow," Journal of Fluid Mechanics, Volume 22, Part 4, pages 721-735, 1965.

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APPENDIX B

SEWER FILTER CHARACTERIZATION PROGRAM

Waste Quality Testing
- Storm Flow Conditions -

Determination	Raw(2) Waste	Strainer Effluent	Concentrated Stream	Strainer Solids
1. pH	d	d	d	
2. Total Solids	d-c	d-c	d	c
3. Total Solids - Volatile	d-c	d-c	d	c
4. Suspended Solids(1)	d	d	d	c
5. Suspended Solids - Volatile(1)	d	d	d	
6. Biochemical Oxygen Demand	d	d	d	
7. Chemical Oxygen Demand	d-c	d-c	d	
8. Particle Size Distribution	d-c	d-c	d	

---

d = discrete samples
c = composite samples

Sampling Frequency - From the study of previous storm flow records at the Bowling Green Waste Treatment Plant, sampling frequency will be as follows: (1) discrete samples - 0, 5, 15, 25, 45, 75, 120 minutes and then hourly thereafter while flow remains significantly above normal and (2) composite samples - 3 samples taken from first 30 minutes, 3 from next 90 minutes, and 3 from the remaining duration.

The quality of the concentrated stream from the filter will be determined by difference between raw waste influent and strainer (filter) effluent with spot checks of the determinations indicated.

At the completion of each test run, the filter will be removed and the deposited and entrapped material analyzed as shown.

(1) Suspended solids determinations will be made using fiberglass filter elements rather than the standard Gooch crucible technique, with occasional spot checks of both methods for comparison.

(2) Samples for quality analysis of the raw waste will be taken just before the flow enters the filter test stand, which is at the plant pump discharge after the waste passes through a screener sized to remove materials larger than 1/4" diameter. This location was chosen to provide a more accurate determination of the filter efficiency while still yielding a good characterization of the plant influent.

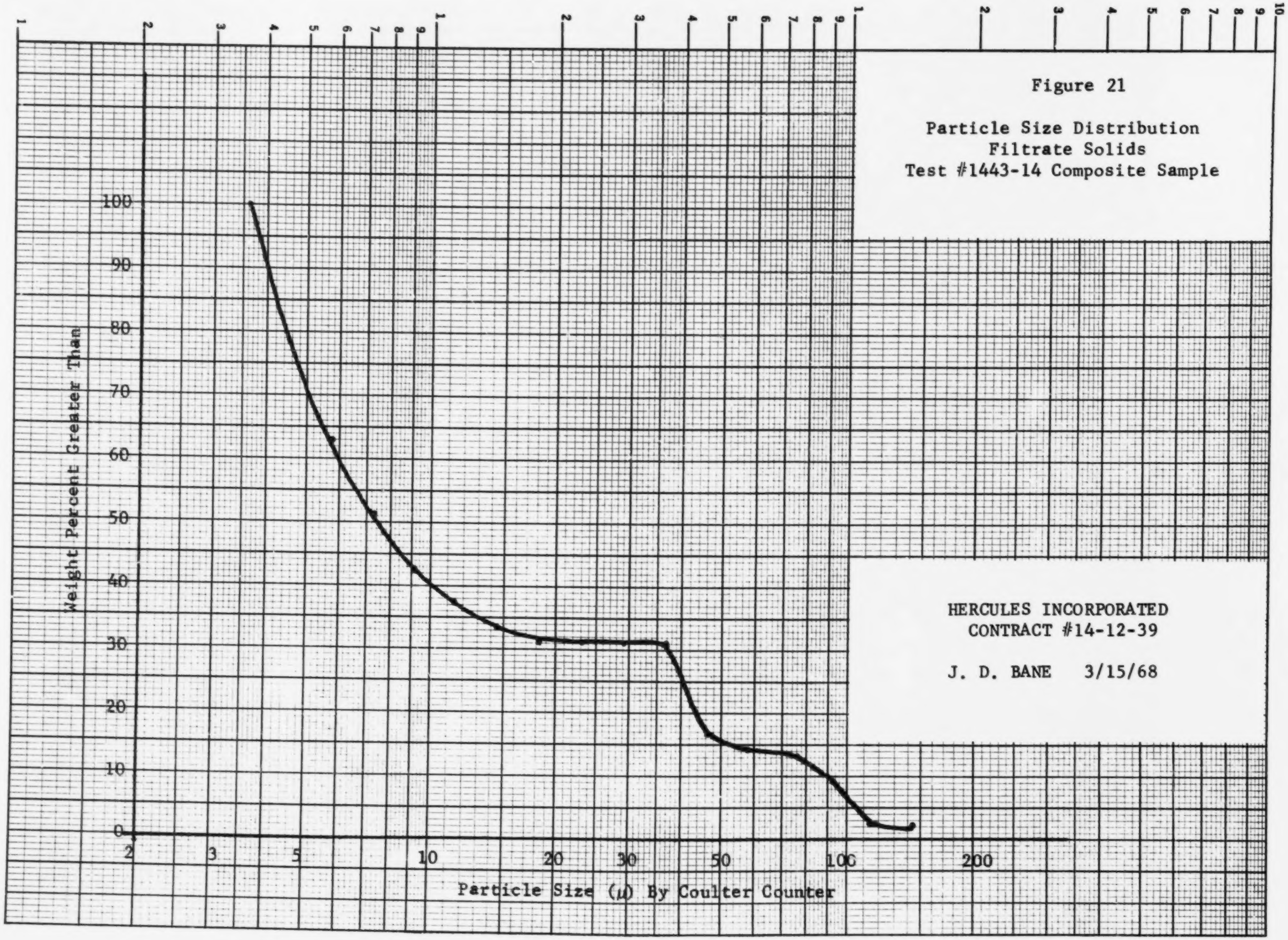
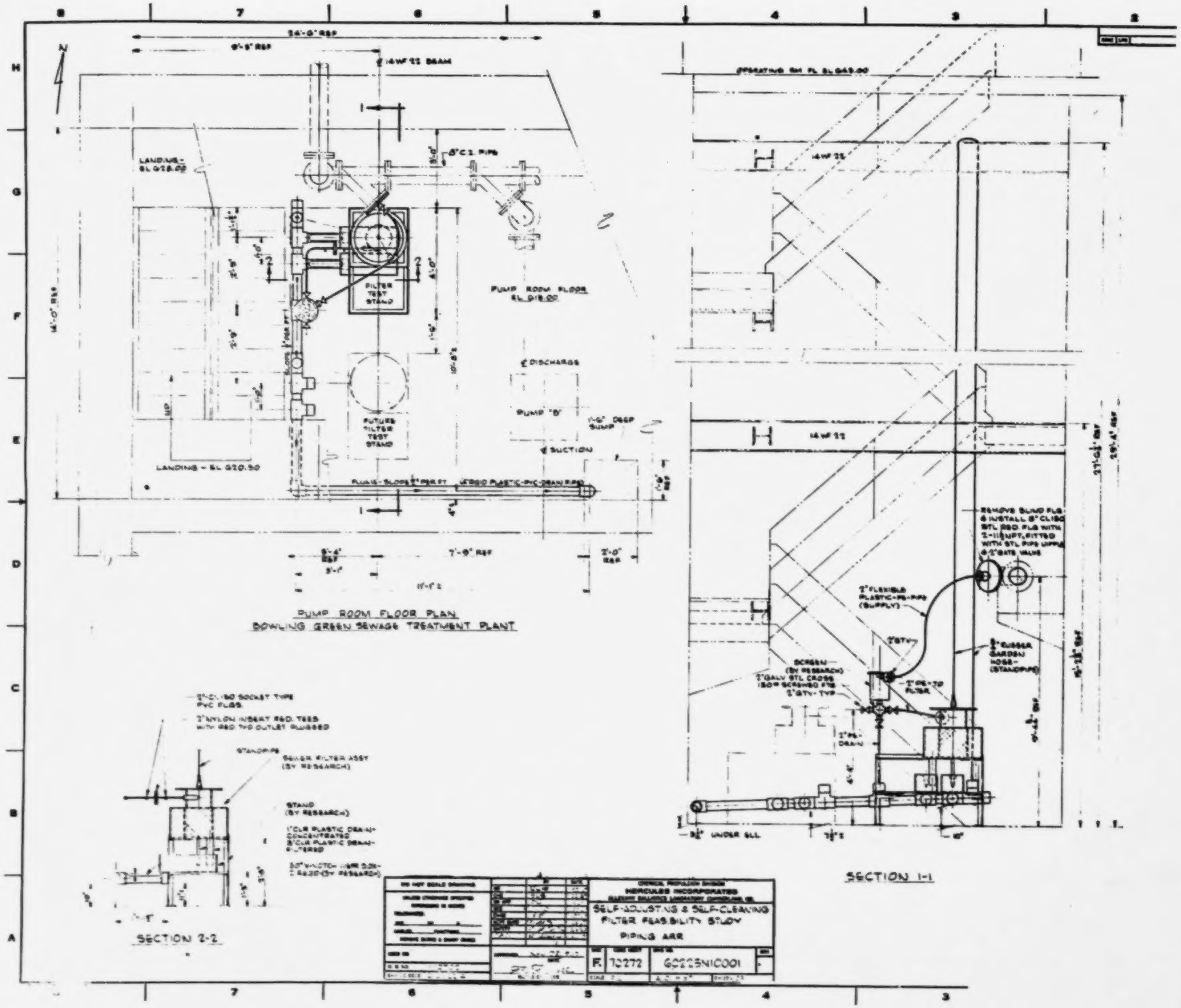


Figure 21

Particle Size Distribution
Filtrate Solids
Test #1443-14 Composite Sample

HERCULES INCORPORATED
CONTRACT #14-12-39

J. D. BANE 3/15/68


PUMP ROOM FLOOR PLAN
BOWLING GREEN SEWAGE TREATMENT PLANT
SECTION 1-1
SECTION 2-2
34'-6" REF
9'-5" REF
14'-0" REF
℄ 14WF 22 BEAM
8" C.I. PIPE
LANDING - EL 628.00
LANDING - EL 620.50
PUMP ROOM FLOOR EL 618.00
FILTER TEST STAND
FUTURE FILTER TEST STAND
℄ DISCHARGE
PUMP "B"
1'-6" DEEP SUMP
℄ SUCTION
7'-9" REF
2'-0" REF
11'-1"
OPERATING RM FL EL 643.00
14WF 22
REMOVE BLIND FLG & INSTALL 8" CL150 STL RED FLG WITH 2-11½NPT, FITTED WITH STL PIPE NIPPLE & 2" GATE VALVE
2" FLEXIBLE PLASTIC-PE-PIPE (SUPPLY)
2" GTV
¾" RUBBER GARDEN HOSE (STANDPIPE)
SCREEN (BY RESEARCH)
2" GALV STL CROSS 150# SCREWED FTG
2" GTV - TYP
2" PE - TO FILTER
2" PE - DRAIN
3½" UNDER SILL
27'-0½" REF
29'-4" REF
2" CL150 SOCKET TYPE PVC FLGS.
2" NYLON INSERT RED. TEES WITH RED TYP OUTLET PLUGGED
STANDPIPE
SEWER FILTER ASSY (BY RESEARCH)
STAND (BY RESEARCH)
1" CLR PLASTIC DRAIN - CONCENTRATED
3" CLR PLASTIC DRAIN - FILTERED
DO NOT SCALE DRAWING
HERCULES INCORPORATED
SELF-ADJUSTING & SELF-CLEANING FILTER FEASIBILITY STUDY
PIPING ARR
F
70272
G0223N1C001

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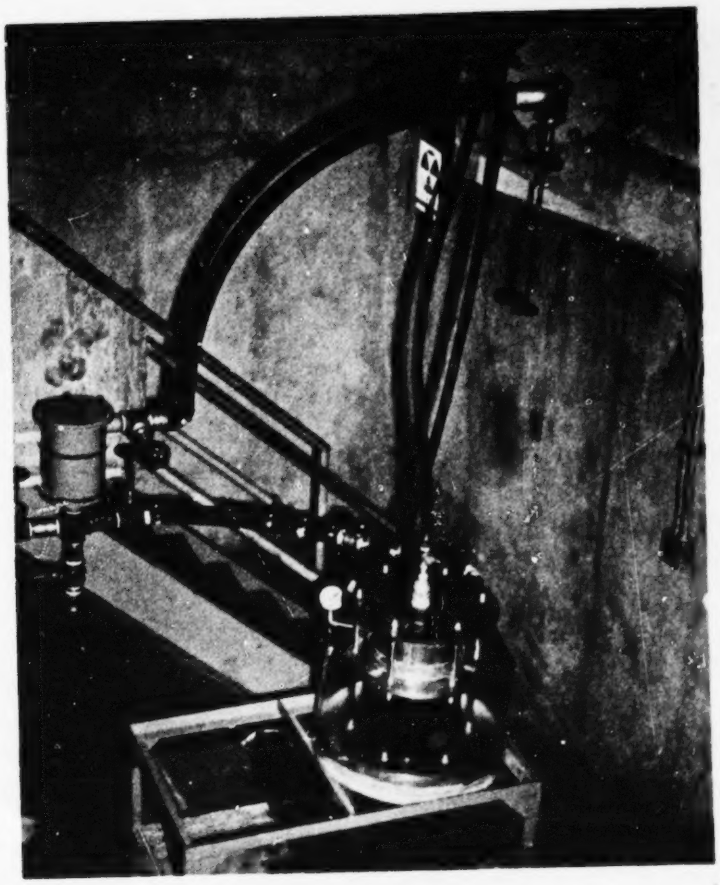

FIGURE 22
Overall Test Arrangement

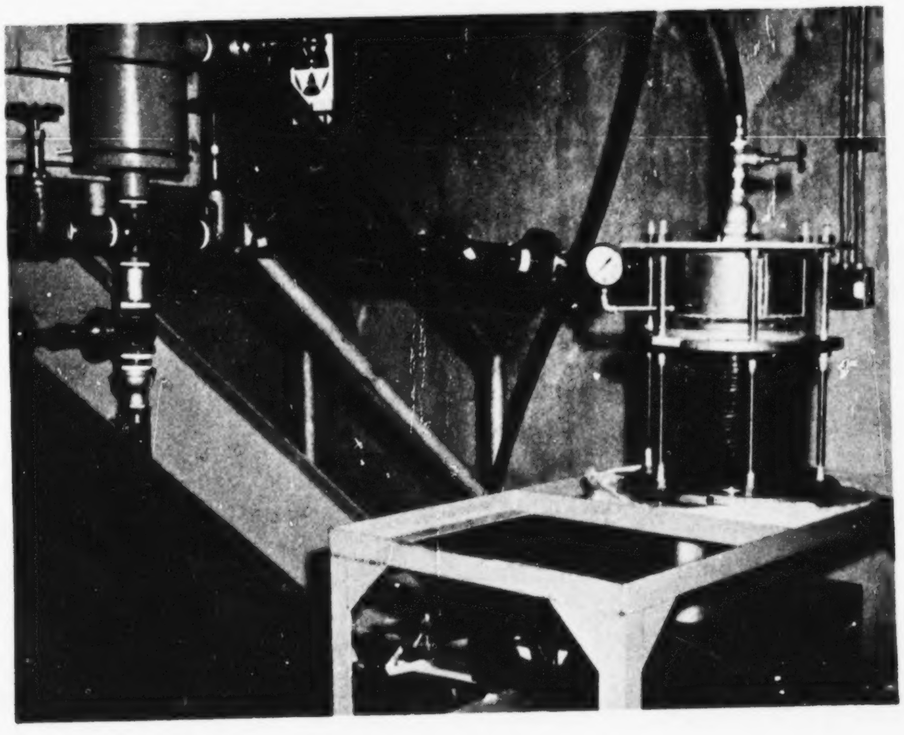

FIGURE 23
Test Stand with Filter

Each filter, after fabrication and crazing, was placed on the test stand at ABL and its filtration rate determined at various hydraulic pressures. The physical changes were also observed for use in checking the calculations made for the filter's fabrication.

The test stand configuration is shown in Figure 24. The cylindrical filter is clamped against the sealing O-rings by the flanges. The tapered doublers fit the clamping flanges so that a tensile load may be applied to the filter if desired. The top plate assembly contains two-inch pipe ports for feeding both tangentially and axially. The bottom plate provides the support for the upper assembly and baffle body, and ports for the filtered and concentrated streams. Valves in the feed and concentrate lines provide the means for adjusting the operating conditions of pressure and volume.

The testing program was directed toward obtaining engineering data on filter operation for evaluation of the test vehicles. It became apparent early in testing that although the data would not be complete, they would indicate trends. These trends would allow a qualitative screening of the effectiveness of various types of filters, baffles, etc.

Since a blank or control was almost impossible to incorporate in the testing, the data from filter testing were reduced partly by direct comparison and partly by experience. This was in part due to the change in sewage and partly due to the differences in the filter fabrication methods. Also, since all filters would partly plug during testing, no constant operating results for an entire run could be obtained. This plugging also prevented using the same filter twice so that a test could not be repeated with exactness. All test data are recorded in Tables 6 through 17.

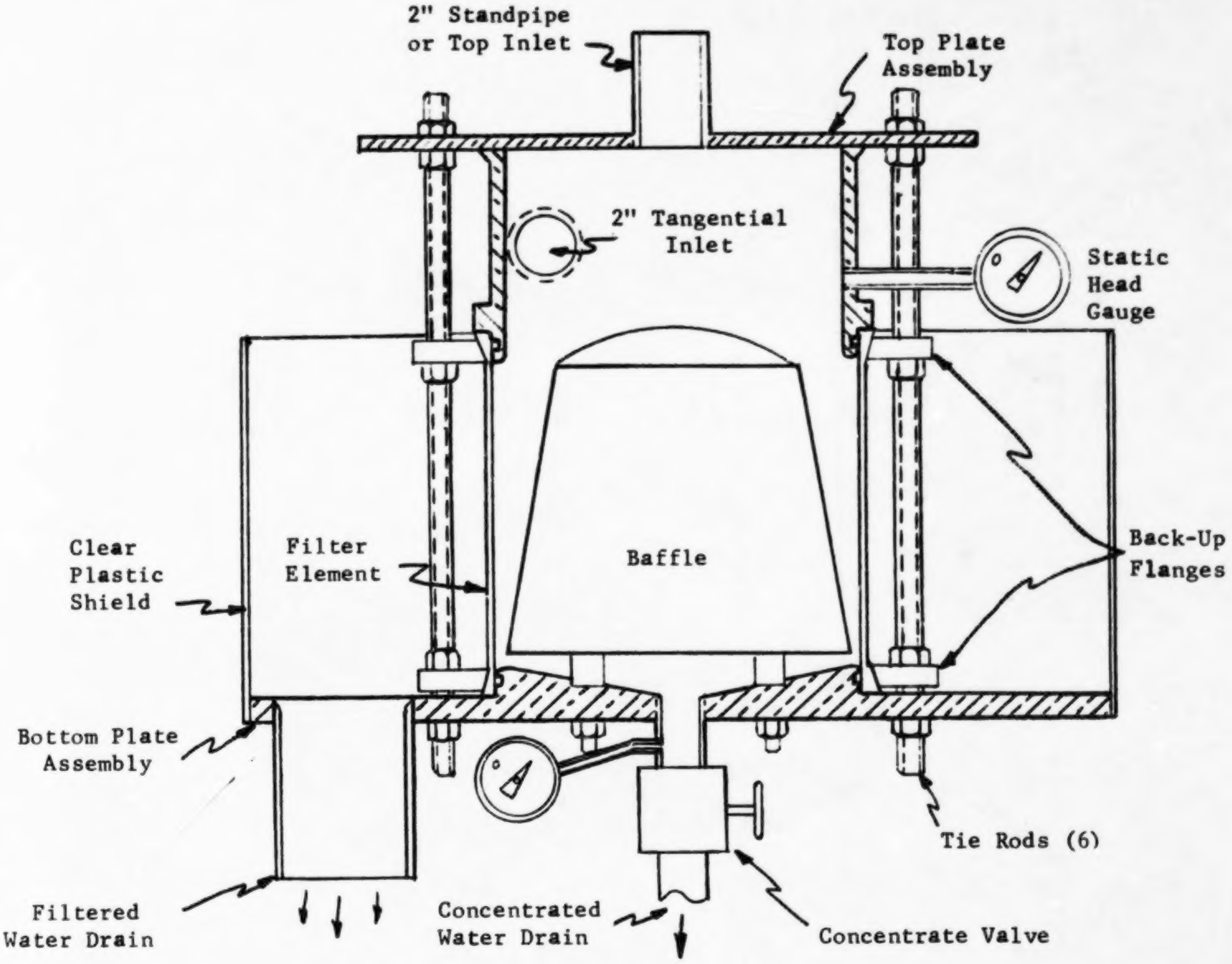
2" Standpipe or Top Inlet
Top Plate Assembly
2" Tangential Inlet
Static Head Gauge
Back-Up Flanges
Clear Plastic Shield
Filter Element
Baffle
Bottom Plate Assembly
Tie Rods (6)
Filtered Water Drain
Concentrated Water Drain
Concentrate Valve

FIGURE 24

Detail Of Sub-Scale Filter Test Assembly

Filter - 04A
Baffle - 11.6 x 10 cone
Feed - Top
Screen - 1/4"

TABLE 6

SEWER FILTER TEST
#1443-6
Date - 1/24/63

Plant Influent - 0.2 MGD
Weather - Cold, Sunny

TEST DATA								ANALYTICAL DATA (mg/liter)								
		Filtrate Flow		Concentrate Flow												
Time (min)	Feed Pressure (psi)	(gpm)	(gpm/ft^2)	(gpm)	(gpm/ft^2)	Bottom Pressure (psi)	Remarks	Source	SS	SS_v	TS	TS_v	BOD	COD	pH	Particle Dist.
5	9	2.5	0.8	15	4.8	-		Raw	120	78	538	145	41.3		7.4	
								Filtrate	48	37	499	74	31.2		7.5	
								Concent.	43	25	434	23			7.2	
10	10	2.5	0.8	14	4.5	7	Raised Pressure	Raw	79	58	126	54			7.6	
								Filtrate	27	21	476	55			7.7	
								Concent.	43	31	482	73			7.5	
15	10.4	1.5	0.5	15	4.8	7										
20	10.5	1	0.3	15	4.8	7										
21	12						Raised Pressure									
25	12.6	2.5	0.8	12	3.8	9.5		Raw	59	40	484	100			7.5	
								Filtrate	27	23	323	18			7.3	Yes(1)
								Concent.	44	36	487	89			7.5	
28	14	3.5	1.1	15	4.8	10.5	Raised Pressure									
30	0															
31	13.2	5	1.6	10	3.2	9	Pressure Cycle #1									
36	13.7	2	0.6	12	3.8	10.5										
37	0															
38	13.7	4	1.3	13	4.1	10.5	Pressure Cycle #2									
43	13.7	1.5	0.5	14	4.5	10.5										
44	0															
0	13.2	10	3.2	11	3.5	10	Water Flush									
0	7.7	3	1.0	14	4.5	4.5	Water Flush									
0	12.5	3.5	1.1	15	4.8	9.2	Sewage Flow									
5	13.5	1.5	0.5	15	4.8	10.2	Test End									

---

(1) 82% by weight particles smaller than 37μ.

TABLE 7

Filter - 04A
Baffle - 11.6 x 10 cone
Feed - Top
Screen - None

SEWER FILTER TEST
#1443-7
Date - 1/31/68

Plant Influent - 0.26 MGD (Controlled)
Weather - Warm, Sunny

TEST DATA								ANALYTICAL DATA (mg/liter)								
Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks	Source	SS	SS_v	TS	TS_v	BOD	COD	pH	Particle Dist.
0	10.5	16	5.1	10	3.2	7.2										
2	11.2	6	1.9	15	4.8	8		Raw	66	33						
								Filtrate	26	17						
								Concent.	34	24						
5	12	4.5	1.4	15	4.8	9										
10	12.2	2	0.6	15	4.8	9		Raw	-	-						
								Filtrate	22	13						
								Concent.	39	30						
10.5	0						Pressure Cycle #1									
11	12.2	5	1.6	15	4.8	9	Dewatering Sample	Filtrate	35	14						
15	12.7	4.5	1.4	15	4.8	9.7										
22	13.5	2	0.6	15	4.8	10.5										
25	14	2	0.6	15	4.8	11										
30	14.2	1.5	0.5	15	4.8	11.5										
31	0						Pressure Cycle #2									
32	14	3	1.0	15	4.8	11										
35	14.5	2	0.6	5	1.6	11.5	Concentrate flow reduced									
40	14.5	1.5	0.5	5	1.6	11.5										
40.5	0															
41	14	1.5	0.5	5	1.6	11	Pressure Cycle #3	Raw	67	44						
								Filtrate	49	32						
								Concent.	64	47						
44	14	1.5	0.5	7	2.2	11	Test End									

Filter- 04B
Baffle - 11.6 x 10 cone
Feed - Top
Screen - None

TABLE 8

SEWER FILTER TEST
#1443-9
Date - 1/31/68

Plant Influent - 0.26 MGD
(Controlled)
Weather - Warm, Sunny

TEST DATA								ANALYTICAL DATA (mg/liter)								
		Filter Flow		Concentrate Flow												
Time (min)	Feed Pressure (psi)	(gpm)	(gpm/ft^2)	(gpm)	(gpm/ft^2)	Bottom Pressure (psi)	Remarks	Source	SS	SS_v	TS	TS_v	BOD	COD	pH	Particle Dist.
2	8	16	5.1	5	1.6	5		Raw	92	72	402	96	22.6	103	7.4	
								Filtrate	35	22	383	79	19.3	72	7.2	Yes(1)
								Concent.	38	27	590	181		72	7.5	
5	10.5	12	3.8	11	3.5	7.2										
8	10.5	7	2.2	10	3.2	7.2										
10	10.8	5	1.6	10	3.2	7.2										
15	10.9	3.5	1.1	10	3.2	7.5		Raw	36	23	414	105		68	7.4	
								Filtrate	24	16	385	93		127	7.4	
								Concent.	34	23	388	97		60	7.6	
20	11.5	3.5	1.1	11	3.5	8										
25	11.8	3	1.0	10	3.2	8.5										
30	11.8	2.5	0.8	10	3.2	8.5		Raw	52	38	397	95	22.7	76	7.5	
								Filtrate	34	23	387	90	22.7	91	7.5	Yes(2)
								Concent.	39	29	403	103	22.6	152	7.5	
40	12.2	1.5	0.5	10	3.2	9										
43	13.2	2.7	0.9	9	2.9	10	Pressure raised									
45	13.2	2	0.6	9	2.9	10.2										
50	13.2	1.5	0.5	11	3.5	10										
51	14.2	2.5	0.8	10	3.2	11	Pressure raised									
55	14.2	2.5	0.8	8	2.5	11										
60	14.2	2	0.6	11	3.5	11		Raw	42	32	424	109		42	7.5	
								Filtrate	33	23	391	93		42	7.6	
								Concent.	43	32	420	123		48	7.5	
61	0						Test End									

---

(1) 88% by weight particles smaller than 37μ.
(2) 93% by weight particles smaller than 37μ.

TABLE 9

Filter - 04B
Baffle - 11.6 x 10 cone
Feed - Top
Screen - None

SEWER FILTER TEST
#1443-9A
Date - 2/15/68

Plant Influent - 0.3 MGD
Weather - Cold, Sunny

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
-	14.2	2	0.6	11	3.5	11	Filtering rate at end of previous test
3	10	3.5	1.1	16	5.1	7	
5	11	1.5	0.5	15	4.8	8	
10	12	1.5	0.5	15	4.8	9	
15	13	1.0	0.3	15	4.8	10	
16	14	1.5	0.5	15	4.8	10	Raised pressure
17	0						Pressure Cycle #1
17.5	14	2	0.6	15	4.8	10	
20	14	1	0.3	15	4.8	10	
20.5	0						Pressure Cycle #2
22	14	1	0.3	15	4.8	10	
23	0						Test End

TABLE 10

SEWER FILTER TEST
#1443-10
Date - 2/12/68

Filter - 02A (Cloth Liner)
Baffle - Deck Plate
Feed - Top
Screen - None

Plant Influent - 0.3 MGD
Weather - Cold, Sunny

TEST DATA								ANALYTICAL DATA (mg/liter)								
		Filtrate Flow		Concentrate Flow												
Time (min)	Feed Pressure (psi)	(gpm)	(gpm/ft^2)	(gpm)	(gpm/ft^2)	Bottom Pressure (psi)	Remarks	Source	SS	SS$_v$	TS	TS$_v$	BOD	COD	pH	Particle Dist.
-	1	18	5.7	-	-		Water Flux Rate Test									
2	5	7	2.2	20	6.4	2										
5	9.5	4	1.3	17	5.4	6		Raw	559	269	570	238			7.5	
								Filtrate	62	42	451	146			7.5	Yes
								Concent.	182	132	531	224			7.3	
10	11.2	1.5	0.5	15	4.8	8										
15	14	1	0.3	17	5.4	11	Raised Pressure									
16	0						Pressure Cycle #1									
17	14	3	1.0	17	5.4	11										
25	10	1	0.3	15	4.8	6	Reduced Pressure									
29	0						Pressure Cycle #2									
30	13	3	1.0	17	5.4	10.5										
34	0						Pressure Cycle #3									
35	14	1.5	0.5	17	5.4	10.5										
39	0						Pressure Cycle #4									
40	14	1	0.3	17	5.4	10.5										
41	0						Test End									

TABLE 11

Filter - 10A
Baffle - 11.6 x 10 cone
Feed - Top
Screen - None

SEWER FILTER TEST
#1443-11
Date - 2/28/68

Plant Influent - 0.23 MGD
Weather - Cold, Clear

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
-	3	10	3.2				Water Flux Rate Test
-	6	10	3.2				Water Flux Rate Test with Hoop Bands
5	12	1	0.3	15	4.8	9	Sewage Test
10	13	.75	0.2	15	4.8	10	
15	13.5	.5	0.2	15	4.8	10.5	
16	0						Pressure Cycle
17	14	1	0.3	15	4.8	10	
20	14						Bands removed
22	10	.5	0.2	11	3.5	7	
25	13	.5	0.2	11	3.5	10	
26	0						Pressure Cycle
27	13.5	1.25	0.4	9	2.9	11	
28	0						Pressure Cycle
30	14	1	0.3	7	2.2	11	
31	0						Test End

ANALYTICAL DATA (mg/liter)

Source	SS	SS$_v$	TS	TS$_v$	BOD	COD	pH	Particle Dist.
Raw	159	136	485	229	51.2		7.25	
Filtrate	55	42	387	143				
Concent.	150	126	487	222				

TABLE 12

SEWER FILTER TEST
#1443-12
Date - 3/1/68

Plant Influent - 0.25 MGD
Weather - Cold, Clear

Filter - 10B with overwinds
Baffle - Ramp & Cylinder & 11.6 x 10 cone
Feed - Top
Screen - None

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow		Concentrate Flow		Bottom Pressure (psi)	Remarks
		(gpm)	(gpm/ft^2)	(gpm)	(gpm/ft^2)		
-	10	10	3.2	-	-		Water Flux Rate Test
5	14	.75	0.2	6	1.9	5	Ramp Baffle
6	0						Test End
0	8.5	.5	0.2	16	5.1	5	Cone Baffle
5	14	.75	0.2	10	3.2	11	
9	0						Pressure Cycle
10	14	.75	0.2	15	4.8	11	
12	0						
-	15	8	2.5	5	1.6	12	Water Flush
	13	6	1.9	5	1.6	10	
0	12.5	.5	0.2	6	1.9	7	Sewage
5	13	.5	0.2	15	4.8	10	
9	0						Pressure Cycle
10	14	.5	0.2	12	3.8	11	
11	0						Test End

TABLE 13

Sewer Filter Test
#1443-13
Date - 3/4/68

Filter - 11A
Baffle - Cones (1) 10 x 11.6 (2) 7 x 11.6
Feed - Top
Screen - None

Plant Influent - 0.3
Weather - Clear, Cold

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
-	5.7	5	1.6	-	-		Water flux rate test
	9.5	10	3.2	-	-		
	13.2	15	4.8	-	-		
0							Cone (1)
5	7	.5	0.2	16	5.1	4	
7	10.5	1.6	0.5	16	5.1	6.5	Raised pressure
10	13	.75	0.2	16	5.1	10	Raised pressure
13.5	0						Pressure cycle
14	14	1.5	0.5	15	4.8	11	
15	14	.5	0.2	15	4.8	11	
15.5	0						Pressure cycle
16	14	.5	0.2	14	4.5	11	
20	0						Test end
-	15	15	4.8	-	-		Water flush
0							Cone (2)
5	12	.1	0.03	15	4.8	8	
7	14	.5	0.2	15	4.8	10	
7.5	0						Pressure cycle
8	13.5	.5	0.2	15	4.8	10	
9.5	0						Pressure cycle
10	14	.5		15	4.8	10	
15	0						Test end

TABLE 14

Sewer Filter Test
#1443-14
Date - 3/14/68

Filter - 12B
Baffle - Cone 7 x 11.6
Feed - Top (added booster pump)
Screen - 1/4"

Plant Influent - 0.45 MGD
Weather - Sunny, Cool

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow		Concentrate Flow		Bottom Pressure (psi)	Remarks
		(gpm)	(gpm/ft^2)	(gpm)	(gpm/ft^2)		
-	15	1.5	0.5	-	-		Water flux
-	20	2.5	0.8	-	-		rate test
0							
5	19	.5	0.2	10	3.2	16	
10	20	.1	0.03	10	3.2	17	
10.5	0						Pressure cycle
15	22	.1	0.03	6	1.9	19	
-	20	1	0.3	-	-		Water flush
-	22	1.5	0.5	-	-		
0	20	.1	0.03	7	2.2	18	
7	21.5	> .1	> 0.03	7	2.2	19	
14							Pressure cycle
15	23	.1	0.03	4	1.3	20	
25	22.5	> .1	> 0.03	3	1.0	20	
26.5	0						Pressure cycle
27	23	.3	0.1	3	1.0	20	
34.5	0						Pressure cycle
35	23	.3	0.1	3	1.0	20	
36	0-23						3 Pressure cycles
37	21	.1	0.03	3	1.0	18	
44	0						Pressure cycle
45	22.5	.2	0.1	3	1.0	20	
55	22.5	> .1	> 0.03	2.5	0.8	20	
60	0						Pressure cycle
61	23	.2	0.1	3	1.0	20	
70	24	> .1	> 0.03	5	1.6	21	
71	0						Pressure cycle
80	23	.1	> 0.03	5	1.6	20	
82	0-23						3 Pressure cycles
83	25	.2	0.1	5	1.6	23	
90	23.5	> .1	> 0.03	5	1.6	21	Test End

TABLE 14 (CONTINUED)

ANALYTICAL DATA

(mg/liter)

Source	SS	SS_v	TS	TS_v	BOD	COD	pH	Particle Dist.
			Composite from Entire Test					
Raw	75	49	630	162				
Filtrate	20	9	650	112				Yes
Concentrate	46	33	657	150				

TABLE 15

Sewer Filter Test
#1443-15
Date - 3/15/58

Filter - 11A (Backflushed)
Baffle - Deck Plate
Feed - Top
Screen - 1/4"

Plant Influent - 0.65 MGD
Weather - Warm, Sunny

TEST DATA

Time (min)	Feed Pressure (psi)	Filter Flow (gpm)	Filter Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
2	8	3.5	1.1	20	6.4	5.5	
4	10	1.5	0.5	17	5.4	6	
5	0						Pressure cycle
5.5	10.5	2	0.6	18	5.7	7	
10	10	1	0.3	18	5.7	7	
10.5	2	1	0.3	17	5.4	7	Open bottom valve
11	0						Pressure cycle
11.5	10	1	0.3	17	5.4	7	
15	10	.7	0.2	17	5.4	7	
15.5	0						Pressure cycle
16	10	.7	0.2	17	5.4	7	
18	10	.5	0.2	17	5.4	7	
20	0						Pressure cycle
22	10	.7	0.2	17	5.4	7	
25	10	.5	0.2	17	5.4	7	
25.5	2						Open bottom valve
27	10	.6	0.2	18	5.7	7	
29	0						5 pressure cycles
30.5	10	1.2	0.4	17	5.4	7	
34	0						Pressure cycle
35	14.5	2	0.6	18	5.7	11.5	
36	14.7	1.5	0.5	18	5.7	11.5	
37	14.7	1	0.3	18	5.7	11.5	
37.5	0						Pressure cycle

TABLE 15 (CONTINUED)

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
38	14.7	1.5	0.5	18	5.7	11.5	
39	14.7	1.0	0.3	18	5.7	11.5	
40	0						5 pressure cycles
42	14.7	1.7	0.5	17	5.4	11.5	
45		1.0	0.3	--	--		
48		0.5	0.2	--	--		
49	0						5 pressure cycles and drain.
50	15	2.5	0.8	15	4.8	12	
52	15	1.5	0.5	15	4.8	12	
53.5	0						Pressure cycle
54	15	1.5	0.5	15	4.8	12	
56	15	0.7	0.2	15	4.8	12	
60	15	0.5	0.2	15	4.8	12	
60.5	0						Pressure cycle
61	15	1	0.3	15	4.8	12	
62							Test End

TABLE 16

Sewer Filter Test
#1443-16
Date - 3/15/68

Filter - 6" Dia. x 6" long
Baffle - Cylinder
Feed - Bottom
Screen - 1/4"

Plant Influent - 0.65 MGD
Weather - Warm, Sunny

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
0	7	2	0.6				
5	9	0.5	0.2				
5.5	0						Pressure cycle
10	10	1.5	0.5				
14	10	.3	0.1				
14.5	0						Pressure cycle
15	10	1.0	0.3				
17	10	0.3	0.1				
18.5	0						Pressure cycle
19	10	1	0.3				
22	10	0.3	0.1	6	1.9		
24	0						Pressure cycle
26	10	0.5	0.2				
28	0						3 Pressure cycles
30	10	1.2	0.4				
32	10	0.2	0.1				
33	15						3 cycles overpressure
34	10	2	0.6				
35	10	0.5	0.2				
36	0						Test End

TABLE 17

Sewer Filter Test
#1443-17
Date - 3/22/68

Filter - 12B
Baffle - Cone 10 x 11.6
Feed - Top (added Booster pump)
Screen - None

Plant Influent - 0.5 MGD
Weather - Warm, Cloudy

TEST DATA

Time (min)	Feed Pressure (psi)	Filtrate Flow (gpm)	Filtrate Flow (gpm/ft^2)	Concentrate Flow (gpm)	Concentrate Flow (gpm/ft^2)	Bottom Pressure (psi)	Remarks
-				-	-		Water flux rate test
				-	-		
-	10	-	-	-	-		Slight weeping
-	14	-	-	-	-		Small streams
-	20	2.5	0.8	-	-		
-	25	5	1.6	-	-		
-	29	10	3.2	-	-		
1	20	1.5	0.5	8	2.5	18	Streams
3	25	1.5	0.5	2	0.6	22.5	Adjust pressure
6	26	1.0	0.3	1	0.3	23	
9	26	0.75	0.2	0.75	0.2	23	Weeping
10	4						Pressure cycle
11	25.5	1	0.3	2	0.6	22.5	Streams
13	25.7	0.75	0.2	1.5	0.5	23	Weeping
13.5	5						Pressure cycle
15	25	.75	0.2	3	1.0	22.5	Few streams
17	0						Pressure cycle
17.5	25	0.75	0.2	2.5	0.8	22	Few streams
21	25.5	0.3	0.1	2	0.6	22.5	Few streams
22	7						Open bottom valve
23	25	0.2	0.1	2	0.6	22	
25	28						Boost pressure with water
26	25.5	0.2	0.1	1.5	0.5	23	
30	0						Test End
.5	30	3	1.0				Water flush
1	0						Pressure cycle
1.5	30	9	2.9				

Fifteen feasibility tests were performed at BGWTP using eleven different filter elements and five swirl baffle bodies. The first tests were conducted using tangential raw sewage feed to produce the swirling turbulent flow described in the proposal. When it was found that the plugging solids appeared to build up on the downstream side of the longitudinal cracks, the sewage was fed to the test stand through the top opening to produce fluid flow parallel to the longitudinal axis of the filter. Feeding parallel to the filter wall noticeably decreased the rate at which the filter blinded. For this reason, most of the tests were run with a nonswirling flow through the filter.

During the early testing it was noted that the screener basket was plugging even though the screen was a ¼-inch mesh. The screen had been intended to remove any large particles which might lodge in the narrow clearances between the filter and the baffles in the sub-scale filter system. Since the strainer did plug and cause a nonconstant feed composition for the filter, the screen was eliminated.

The first filters tested contained a limited number of cracks in the gel coat. These few wide cracks allowed a filtration rate of 7 to 12 gpm/ft^2 at 10 psi or less. During the tests with raw sewage, filtration rates remained high several minutes and then began dropping, usually to 1 gpm/ft^2 or less after ten minutes of operation. The filtration rate could be restored somewhat by increasing the operating feed pressure, by flushing with clear water, or by cycling the feed pressure to zero and back to operating pressure. The mechanism of the latter method is attributed to dewatering of the trapped solids which passed on through the wall at repressurization.

At the end of each test, the filters were removed and examined. The interior walls showed no signs of deposit or build-ups other than the material, mostly fibers, in the large cracks. Several filters which contained fine pores were tested later. The filtration rate results with these filters showed very little change from earlier filters in the rate at which plugging occurred but, of far more importance, the character of the plugging material changed. Few fibers were found trapped in these fine pores.

Comparison of the results obtained with the swirl baffle bodies yielded the following findings: (1) Fluid turbulence at the filter surface did not reduce the plugging rate. (2) High fluid velocities reduced the plugging rate. (3) Fluid flow parallel to the major axis of the filter reduced the solids build-up.

One filter (04B) was allowed to dry out with the entrapped material left in place. When testing of this filter was begun again, the filtration rate (3.5 gpm at 10 psi) was higher than the rate before drying (2 gpm at 14 psi), indicating that the dried material did not cause permanent blinding of the pores.

Analytical data (Table 18) from the testing show a suspended solids removal from the filtrate of up to 70%.

TABLE 18

SUSPENDED SOLIDS REMOVAL SUMMARY

Filter Number	Raw Feed Susp. Solids mg/l	Raw Feed Susp. Solids Volat. mg/l	Filtrate Susp. Solids mg/l	Filtrate Susp. Solids Volat. mg/l	Eff. (%)
04A	120	78	48	37	60
	79	58	27	21	66
	59	40	27	23	54
04A	66	33	26	17	61
04B	92	72	35	22	62
	36	23	24	16	33
	52	38	34	23	34
	42	32	33	23	22
10A	159	136	55	42	65
12B	75	49	20	9	73

This efficiency could be reached using both the coarse and finely crazed filters. However, the results of the particle size distribution analyses suggest a great difference in the character of the filtrate solids. Figures 18 and 19 illustrate the particle size distribution from filters with coarse openings, while Figures 20 and 21 are plots of fine pore filtrate particle size distribution. It should be noted that approximately 75% of the solids by weight passed by the fine pore structures are 37 μ (0.0015 inch) or less in diameter.

The feasibility of filter 04B was tested during storm flow conditions at the treatment plant. The influent flow rate was being controlled, causing the feeder lines to act as a surge tank and allowing some sewage to overflow and by pass treatment. The sewage test (#1443-9) lasted one hour. Flow was maintained by raising the feed pressure when the rate reached 0.5 gpm/ft^2. After two minutes, the filtration rate at 8 psi was still above 5 gpm/ft^2 and operation required only 1 gallon of concentrate per 3 gallons of filtrate. A suspended solids removal of 60% was achieved. Gradual plugging required increasing the concentrate flow to maintain the pressure below 15 psi (the upper design limit for operation of this filter). At the end of the test, the filtration rate was below 0.5 gpm/ft^2 at 14.2 psi. The cracks in the gel coat were plugged with fibers that were hooked in the openings, but the buildup was quite shallow and the remainder of the filter interior was clean. This test indicated that the openings must be finer to prevent fibrous blinding of the pores.

The filters which showed the greatest promise of fulfilling the study goals were made in a polar winding pattern. A 6-inch-diameter, 6-inch-long filter element was polar wound using 6 plies of fiberglass composed of 100 strands (20400 filaments) per inch of surface. This filter was mechanically crazed by flexing parallel to the axis of the cylinder. The structure would pass 25 gpm/ft^2 of tap water at 4 psi and essentially 0 gpm/ft^2 at 1 psi. The sewage filtration test (#1443-16) showed an early filtration rate of only 0.6 gpm/ft^2 at 7 psi and rapid plugging. However, an overpressurization cycle completely restored this rate,indicating solids could be completely removed. The filtration effectiveness was determined by comparing the filtrate and concentrate visually. The concentrate was grey in color and loaded with fine particles while the filtrate was clear with no visual particles. Filter 12B was fabricated by hand laying two layers of 1-inch-wide preimpregnated fiberglass unidirectional tape on the mandrel at 0° with 90° overwinds of the polyester fiber. Two layers were necessary to prevent gaps in the structure. Mechanical flexing produced fine cracks in the structure. Due to the fabrication method, the resulting filter required a high pressure to operate. Filtration rates of 0.8 gpm/ft^2 at 20 psi and 3 gpm at 30 psi were reached with tap water. The initial rate with sewage was 0.5 gpm/ft^2 at 20 psi (Test #1443-17). Even though filtration rates were low and plugging occurred rapidly, this filter is believed to offer great potential. By reducing the modulus of the structure or increasing the diameter, the filter will be capable of operating at lower pressure. A thinner wall will enable production of a higher number of fine crazings and should allow the fine particles that enter the pores to pass through more readily. Figure 25 shows the filter as it appeared after feasibility testing. The fine cracks are partially plugged with fine solids and very few fibers. Figure 26 shows the filter pressurized to 30 psi. The fine sprays are indicative of the pore size.

A summary of the filter feasibility testing is shown in Table 19.

This evaluation brings out several points. Filter 04B produced good flow but plugged with fibers which could never be made to pass the filter. Both the 6 x 6 filter and the filter 12B plugged, but not with fibers. All the filters showed good filtering efficiency. Plugging of the fine pore filters could be relieved by overpressurization or by passing the particles through the filter. While not demonstrated, the results indicate that a polar wound structure can be made with the following characteristics: (1) thin enough to craze in fine patterns with a short, less-tortuous path for less trapping of particles, (2) capable of high filtration rate, (3) strong enough to limit the amount of opening

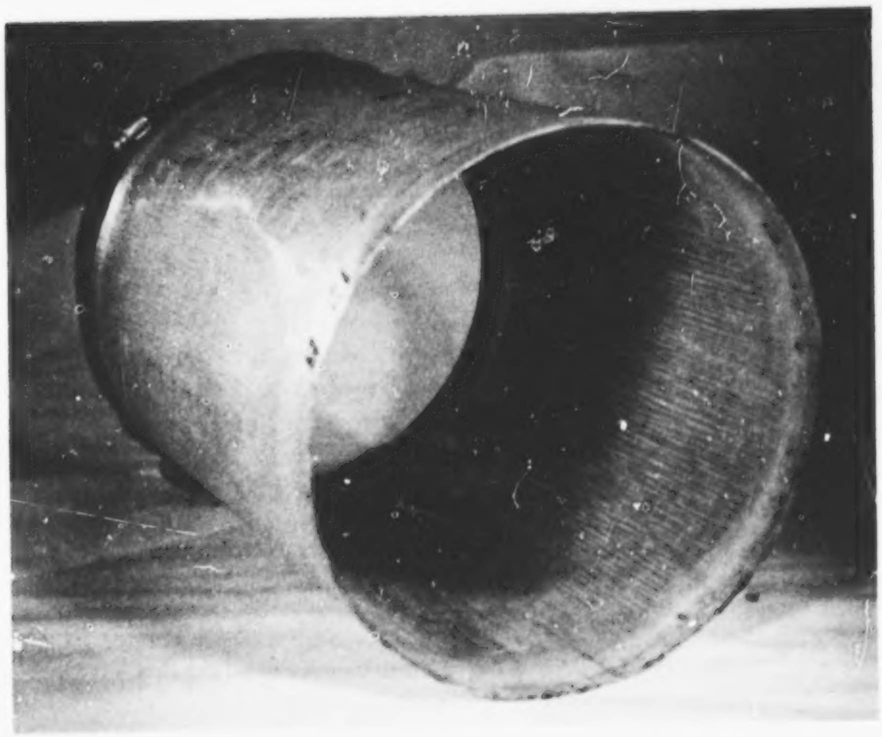

FIGURE 25
Filter 12B (After Testing)

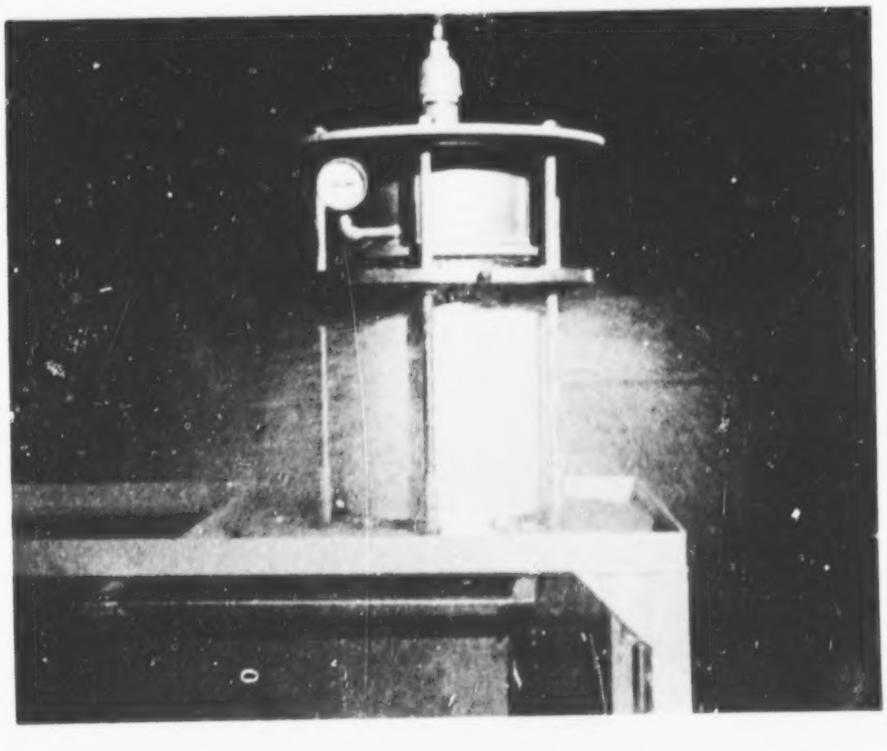

FIGURE 26
Filter 12B (Pressurized)

TABLE 19

SUMMARY OF FILTER FEASIBILITY TEST RESULTS

Test No.	Filter	Baffle	Results
1443-6 (Normal sewage flow)	04A	11.6 x 10 Cone	Low filtration rate and good suspended solids removal. Pressure cycling relieved blinding somewhat but large gel coat cracks trapped fibers.
1443-7 (Storm flow conditions)	04A	11.6 x 10 Cones	High filtration rate and medium suspended solids removal. Pressure cycling relieved blinding somewhat but cracks trapped fibers.
1443-9 (Storm flow conditions)	04B	11.6 x 10 Cone	Very high filtration rate at start and fair suspended solids removal. One hour continuous test before cracks trapped fibers.
1443-9A (Slightly above normal flow)	04B	11.6 x 10 Cone	Tested to determine filtration rate after trapped solids dried in place. Plugging was not complete but rate could not be restored by cycling.
1443-10 (Slightly above normal flow)	02A (cloth liner)	Deck Plate	Rigid controlled pore cloth liner. Low filtration rate which could not be restored.
1443-11 (Normal sewage flow)	10A	11.6 x 10 Cone	Low filtration rate, fiber plugging could not be eliminated.
1443-12 (Normal sewage flow)	10B	Ramp & Cylinder and 11.6 x 10 Cone	Low filtration rate, fiber plugging could not be eliminated.
1443-13 (Slightly above normal flow)	11A	11.6 x 10 Cone and 11.6 x 7 Cone	Low filtration rate, fiber plugging relieved somewhat by water flushing.
1443-14 (Storm flow conditions)	12B	11.6 x 7 Cone	Low filtration rate, blinding occurred rapidly and high suspended solids removal, but pores blinded with small particles and relatively few fibers.

TABLE 19(Cont)

SUMMARY OF FILTER FEASIBILITY TEST RESULTS

Test No.	Filter	Baffle	Results
1443-15 (Storm flow conditions)	11A (Back flushed)	Deck Plate	Low filtration rate and blinding occurred rapidly, but could be relieved somewhat by cycling. Fibers trapped in cracks.
1443-16 (Storm flow conditions)	6" x 6"	Cylinder	High initial filtration rate but blinding occurred rapidly. Plugging relieved by pressure cycling and overpressurization.
1443-17 (Storm flow conditions)	12B	11.6 x 10 Cone	Low capacity pump added; low filtration rate;could relieve blinding somewhat but pores plugged with fine particles and very few fibers.

of the pores, (4) pores which will not trap fibers and (5) capable of regeneration by overpressurization to remove solid particles. For these reasons, Filter 12B is probably the best unit produced and offers the route to development of a working unit. Accordingly, further experimental evaluation of thin-wall filters with fine pores is recommended. Such filters tested over a range of flow conditions (including both laminar and turbulent) should establish whether or not the self-cleaning feature can be realized.

Filtration Plant Costs

Data generated during the performance of this work were not sufficient to allow design and costing of a complete filter plant utilizing the self-adjusting self-cleaning filter. However, a rough order of magnitude cost can be projected to allow preliminary evaluation of the system. These assumptions are based on the best information we have at this time.

From what we now know, large filters would be costly to fabricate and would be too space consuming in actual operation. A large filter would also require a heavier wall which would mean more material per square foot of filter area and a greater flow resistance. Thus, for this cost projection, an element size of one to three feet in diameter will be considered. Again, due to manufacturing cost considerations, length will be limited to about six feet.

The individual filter elements will be most easily handled if they are grouped in a cluster. It is assumed that the ideal plant configuration would be a two-section tank with half of the filter capacity on each section. In-flow is assumed to be pump assisted to generate the necessary head during storm flow conditions, thus allowing a gravity outflow. During dry flow only half the area would be used, allowing maintenance of the other half. With the elements clustered in groups of four to seven on individual holders, through-flow could be directed into separate drains located under each element while filtered flow would be collected from the total area under the filters. A bridge crane would be required to lift a cluster of elements in and out for maintenance in a large plant.

The basis for cost calculations will be as follows:

(1) Sewer flow during storm conditions will be increased by a factor of 10.

(2) Filter flux is estimated to be 7 gpm per ft^2.

(3) Filter life is assumed to be one year.

(4) Elements will be clustered when a large number is used.

(5) Elements will be right cylinders 2 ft. diameter by 6 ft. long.

(6) Elements will support their own center bodies and will require no other flow orientating arrangement.

A filter system for the Bowling Green Waste Treatment Plant would be a typical small setup. For this plant, which has a dry weather flow of 0.1 mgd and a storm flow of 1 mgd, three filter elements would be needed. These would be installed in a metal filter holder and would be operated at a positive pressure. A pump would be required to develop the operating pressure. The pump house-filter area would require a floor space of 10 x 12 feet and estimated cost would be in the neighborhood of $30,000, most of which would be for the building and associated piping. Assuming only 1 year filter life, operating cost would be about $950 per year for filter replacement.

No costs are given for all sizes of treatment plants because the estimated costs are not accurate enough to allow a firm engineering evaluation. For example, a lower filter flow rate would necessitate a larger plant and a proportionally larger capital cost and operating cost. A longer service life on the filter would allow a correspondingly lower operating cost. Both of these factors would affect the costs in a nearly linear fashion.

Naturally, as the size of the plant increases, the cost per 1000 gallon capacity would decrease. In a large plant, operating expenses would be expected to be $0.01 to $0.02 per 1000 gallons of normal plant flow, but firm costs must await results from a demonstration plant setup.

GLOSSARY

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
Catalyst D	A curing catalyst for epoxy resin, Shell Chemical Co.
Concentrate	Fluid retained within the filtering element
Crazing	Random hairline cracks in a resin matrix
Crossover	The point on a helically wound structure at which the plus angle filaments interweave with the minus filaments
Denier	Grams weight of 9000 meters of roving or yarn
DETA	Curing catalyst for epoxy resin
Doubler	An area on a filament wound composite structure reinforced for special load bearing
Epoxy Resin	Synthetic organic resin characterized by two or more ring structures of two carbon and one oxygen atoms
Epon 826	Epoxy resin, Shell Chemical Co.
Epon 953	Flexibilized epoxy resin, Shell Chemical Co.
End	A group of filaments parallel to each other, usually 50 to 204 in these particular fabrications
Filament	A single fiber of material, usually 0.01 inch diameter or smaller
Filtrate	Fluid which passes through the filter surface

GLOSSARY (CONT)

GPM	Gallons per minute
Helical winding	Filament winding technique that places filaments in a helical pattern on a surface of revolution
Helix angle	Angle of the filaments to the central longitudinal axis of the structure
MGD	Millions gallons per day
Micromechanical analysis	Prediction of composite structure behavior from the knowledge of constituent stress-strain properties
Ply	Filaments placed on a surface in a single filament thickness
Polar winding	Filament winding technique in which all filaments are parallel over a surface without interweaving between plies
Polyester	Synthetic polymer produced from reaction of ethylene glycol and terephthalic acid or its derivatives
Polypropylene	Synthetic long chain polymer produced by polymerization of propylene (C_3H_6)
Psi	Pounds per square inch
Roving	One or more ends bundled together in parallel without twist
Winding layer	A complete covering of the surface with filaments placed at the plus (+) and minus (-) helix angle
Yarn	One or more twisted ends (or strands) which are twisted together
ZZL-0803	A curing catalyst for epoxy resin, Union Carbide Co.

BIBLIOGRAPHIC: Hercules Incorporated Allegany Ballistics Laboratory Cumberland, Maryland. Crazed Resin Filtration of Combined Sewer Overflows FWPCA Publication DAST-4 1968.

ABSTRACT: The feasibility of developing a self-cleaning, self-adjusting filtering device constructed of cylindrical structures of fibers laid down in predetermined patterns by a winding process and bonded in place by resins was investigated. The permeability of the structure is imparted by a mechanical cracking or crazing of the resin. Filtration runs showed a 62% reduction of suspended solids in the filtrate. However, sustained runs could not be realized. The self-cleaning aspect was not demonstrated. This report was submitted in fulfillment of Contract No. 14-12-39 between the Federal Water Pollution Control Administration and Hercules Incorporated.

ACCESSION No.

KEY WORDS

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Resin

Crazing

Volume Reduction

Pollutant Concentration

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